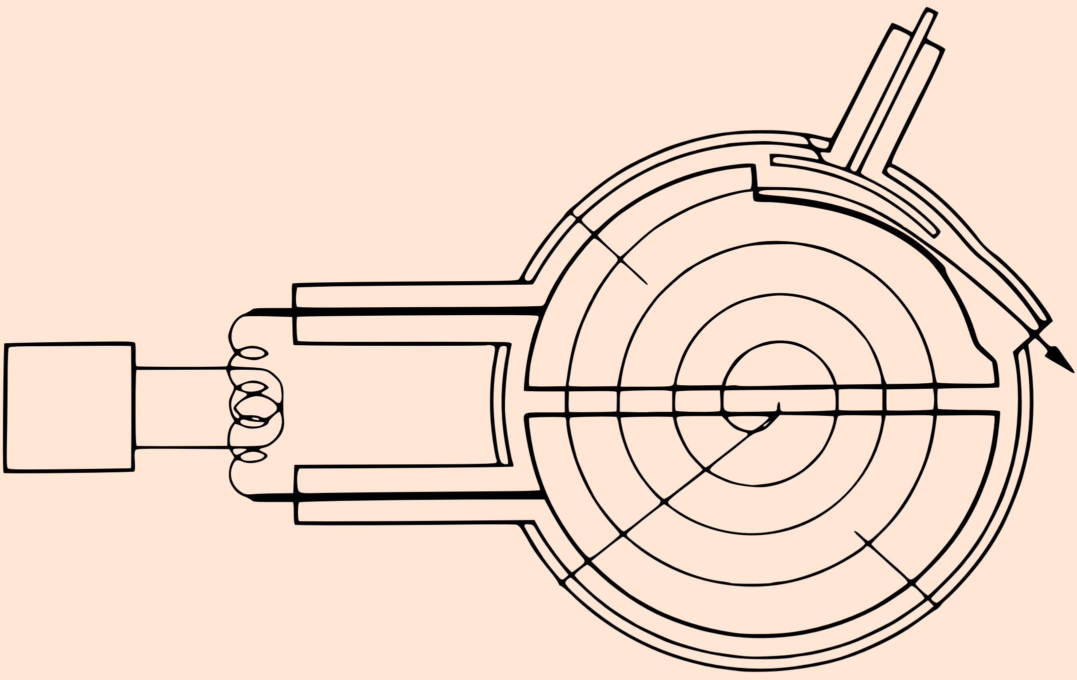
B. S. Ratner

ACCELERATORS OF CHARGED PARTICLES



ACCELERATORS OF CHARGED PARTICLES

ACCELERATORS OF CHARGED PARTICLES

B. S. RATNER

Translated by

L. A. FENN

Translation edited by

H. W. CURTIS

A Pergamon Press Book

THE MACMILLAN COMPANY
NEW YORK
1964

THE MACMILLAN COMPANY
60 Fifth Avenue
New York 11, N.Y.

This book is distributed by
THE MACMILLAN COMPANY
pursuant to a special arrangement with
PERGAMON PRESS LIMITED
Oxford, England

This is a translation of the original Russian *Uskoriteli zaryazhennykh chastits*, published in 1960 by Fizmatgiz, Moscow

Library of Congress Catalog Card Number 63-10061

Printed in Poland
PWN—DRP

TABLE OF CONTENTS

PUBLISHER'S NOTE

THIS book sets out in easily comprehensible form both the history and the latest achievements of accelerator technology, explains the fundamental principles on which accelerators work, and gives the necessary information about the structure of the atom and the atomic nucleus and the main types of nuclear reaction. It is intended for a wide reading public which has no specialized training.

INTRODUCTION

Is IT possible to break up the atomic nucleus? Any schoolboy nowadays would unhesitatingly answer: "Of course!" For since 1954, not far from Moscow, the first nuclear power station in the world has been at work, using the energy set free in the splitting of the nucleus of the heavy metal uranium; and a second, more powerful, nuclear station is already producing current for the requirements of the national economy. The Lenin—the first ice-breaker in the world to be driven by nuclear power—has been built in the Soviet Union, and in the U.S.A. the Savannah, an atomic passenger liner, has been planned and is under construction.

The radioactive substances produced in the splitting of atomic nuclei are being applied in many ways. These substances are used in medicine and biology, industry and agriculture. Cancerous growths are being treated by nuclear radiation and by isotopes. The wear of the friction surfaces of machines is being measured. Food-stuffs are being sterilized and the ages of archeological excavations are being determined. But all this is only the beginning. Mankind has only just reached the threshold of the age of atomic energy. The application of nuclear power will embrace ever more and more aspects of human activity.

At the present time scientists of many countries are at work on the fundamental problem of producing a controlled thermonuclear reaction. The solution of this very difficult problem will make available the inexhaustible source of energy contained in the nucleus of hydrogen, the lightest of the elements. The boldest plans for changing the nature of our planet will become realizable...

Yet only fifty years ago not a single physicist could have answered the question about the splitting of the atomic nucleus, for the simple reason that nobody knew even that the atomic nucleus existed. Thus in not more than a few decades the most startling progress has been made in our knowledge of the world of atoms and atomic particles—a world of the infinitesimally small. A new branch of science—atomic physics—has been created, and its creation has been followed by a rapid development of nuclear technology.

Of especial significance for the development of nuclear physics was the discovery that it was possible to transmute the elements. The bombardment of the nuclei of different elements by fast charged particles enabled us to determine the composition and properties of these nuclei. New methods of penetrating the atomic nucleus were quickly found. The neutron—a particle which, along with the proton, enters into the composition of the nucleus, and which was destined to play a tremendous part in the practical utilization of atomic energy—was discovered. The arsenal of nuclear missiles increased, and apparatus for splitting the atomic nucleus became steadily more and more complicated. Although the first instruments for this purpose could be easily accommodated on the laboratory bench, their successors today—the accelerators of charged particles—reach enormous dimensions. They occupy whole buildings and weigh thousands of tons. Even mightier equipment is being planned. These will enable scientists to probe even deeper into the secrets of the structure of matter, and thereby make even better use of the forces of nature for the development of human society. This book tells the story, in a popular form, of the discovery of methods for the artificial transformation of the elements, of the development of acceleration techniques and the resulting achievements of physics.

CHAPTER I

THE SECRET RECESSES OF MATTER

1. THE STRUCTURE OF THE ATOM

What is the composition of the matter which makes up the Universe? This question is not new. Learned men were preoccupied with this subject even in remote antiquity. More than two thousand years ago the great Greek philosophical materialist Democritus first expressed the idea of the existence of minute indivisible particles of matter. If we begin to divide a piece of solid matter into smaller and smaller particles, he argued, then a time will come when further division is impossible. Thus we reach the ultimate indivisible particles of matter —the atoms ("atomos" in Greek means "indivisible"). The atoms are hard, eternal and indestructible. The world consists of atoms and the space between them. "Just as tragedy and comedy can be written with the same letters, so also all the varied forms which occur in the world are made from the same identical atoms, though they have different positions and perform different motions". However, the majority of the old philosophers did not share the view of Democritus and his disciples. Following Aristotle, whose authority was very great, they denied the possibility of the existence of atoms. Only at the time of the Renaissance, more than seventeen hundred years later, when science began to develop more vigorously, did learned men remember Democritus and his argument about the atomic structure of matter. Unlike the Greeks, for whom the atom was an abstract conception, the scientists of the seventeenth century—Gassendi, Boyle, Newton—tried to explain the actual physical and chemical properties of bodies by means of atomic theory.

The further development of science, associated with the names of Lomonosov, Lavoisier, Dalton and other scientific men, has confirmed the brilliant guess of the ancient philosophers. It has turned out that the atoms of a comparatively small number of simple substances—the elements—actually exist in nature (at the present time 102 elements have been discovered). It is, in fact, the atoms which determine the chemical properties of the elements, i.e. their power of entering into combination with other elements. The great Russian chemist D. I. Mendeleyev discovered in 1869 the law which explains why this or that element possesses definite chemical and physical properties. He showed that the principal characteristic of an element is its atomic weight, i.e. the ratio of the mass of its atom to the mass of an atom of hydrogen, or, more exactly, to 1/16 of the mass of an atom of oxygen. Arranging all the elements known at that time in order of increasing atomic weight, Mendeleyev showed that a clear periodicity existed in their properties. The elements in each column of the system thus constructed proved to have similar chemical properties. Mendeleyev's periodic law formed the basis for the further development of atomic physics. A far-reaching connection was subsequently discovered between this law and the structure of the atom.

The molecule of a compound substance is a combination of individual atoms. The number of different molecules in nature is enormous. At the present time they are counted in hundreds of thousands. Such physical properties of matter as taste, colour, smell and melting point are determined by the composition of the molecules and the positions of the atoms within them.

Although the reality of atoms had been firmly established by the end of the nineteenth century, little more could be said about their structure than in the time of Democritus. "The atom was regarded as indivisible. It was considered to be the last frontier, beyond which the very nature of things forbade us to pass. The atom was looked upon as something indivisible,

impenetrable, eternal, not subject to the influence of either heat or electricity... The interior of the atom was declared to be a territory into which physics would never succeed in penetrating..." So wrote the English physicist J. J. Thomson.

The first serious blow to this view arose from the discovery of the electron. The phenomena of electrolysis, already investigated by Faraday, indicated the probable existence of "atoms of electricity" and their connection with the atoms of the chemical elements. However, free "atoms of electricity"—electrons—were discovered considerably later, in the study of the passage of electric current through gases. Experiments showed that the electrons carried a negative electric charge. The mass of the electron was also found, and turned out to be 1836 times less than the mass of the atom of hydrogen. But how were the electrons bound to the atoms of matter? It was assumed that the electrons entered in some way into the composition of the atom. At the same time, as was well known, the atom as a whole in its ordinary state behaved like a neutral, electrically uncharged body. Hence it followed that there must exist in the atom a positive charge which apparently exactly balanced the action of the negative charge. But how the positive and negative charges were distributed in the atom, what its structure was, remained unclear.

Furthermore, at that time—at the very end of the nineteenth century—it seemed that experiment would be powerless to answer these questions. The dimensions of the atom were already known: they were equal to the hundred millionth part of a centimetre (10^{-8} cm). This means that in the length of a page of this book about twenty milliards of atoms could be placed in a row.* Such objects could not be observed in any microscope, since the microscope enables us to distinguish only those objects whose dimensions are greater than the wavelength of the light used to observe them. The wavelength of visible light (λ) is from 4×10^{-5} to 7×10^{-5} cm, i.e. much

* 1 milliard = one thousand million = 10^8. [Translator]

greater than the dimensions of the atom. Even the comparatively recently constructed electron microscope ($\lambda \cong 10^{-8}$ cm) does not make it possible to observe the structure of the atom, although it has been successfully applied to the study of the structure of molecules.

Having no experimental data relating to the structure of the atom, scientists made use of a picture of the atomic structure proposed by J. J. Thomson. According to this model the positive charge was distributed more or less uniformly throughout the volume of the atom, and the negative charge—the electrons—was sprinkled about in the positive charge at separate points.

After rather more than ten years, however, it appeared that in spite of the very minute dimensions of the atom it was actually possible to study its structure experimentally. When these experiments had been carried out, it became clear that the structure of the atom was quite different from what physicists had supposed.

Not long before this, in 1895, the German physicist Röntgen had discovered rays which possessed the hitherto unknown power of passing easily through comparatively thick layers of matter. Photographic plates, carefully wrapped in several layers of black paper, were blackened after being placed in a beam of these rays, which were called Röntgen rays. The Röntgen rays appeared when fast electrons impinged upon different substances. Neither the electric nor the magnetic field influenced the direction of these rays. This behaviour enabled physicists to determine the nature of the Röntgen rays; they were similar to light—electro-magnetic waves, but with a wavelength thousands of times less. Correspondingly, the energy of the Röntgen rays is much greater than that of light rays, and this explains their peculiar properties.

A year later a new and still more extraordinary phenomenon amazed the world. Becquerel, in France, discovered that the close proximity of substances containing uranium caused blackening of photographic plates wrapped in light-proof paper.

The new phenomenon was called radioactivity. Many physicists were interested in it and began to investigate it, among them Marie and Pierre Curie. After a year of intense work they succeeded in separating from uranium ore a substance which possessed enormous radioactivity, millions of times greater than uranium. This consisted of the new elements—radium and polonium.

But what were these radiations? How was radioactivity connected with the structure of matter? A new mystery of nature demanded explanation.

Here we must mention one further property of the rays, which helped to explain their nature. These rays strongly ionized the medium through which they passed. This means that individual molecules of matter, lying in their path, lose electrons and become positively charged ions. This power of ionization is also possessed by Röntgen rays and by fast electrons. Making use of this ionization effect in the study of radium, physicists succeeded in establishing the fact that the radiation from radium consisted of rays of two kinds, which differed greatly in their power of passing through matter. The weakly penetrating rays (they are completely absorbed by a sheet of thin paper) were called α-rays. Those with greater penetrating power (in order to stop them several millimetres of matter were required) were called β-rays (α and β are the first letters of the Greek alphabet).

The English physicist Rutherford (1871–1937), whose name is associated with remarkable discoveries in the realm of atomic physics, suggested that the α-rays emitted by radium were atoms of some already existing element. In order to verify his hypothesis, it was necessary for Rutherford to determine the mass of the α-particles. For this purpose he carried out the following simple experiment. The electroscope *D* was placed in the upper part of the small chamber *A* (Fig. 1), on the bottom of which the radioactive salt P was situated. The chamber *A* was divided by metal plates placed parallel and close to each other. The α-particles, passing between the metal

plates, produced ionization of the gas within the electroscope (Fig. 1, II) and consequently a change in the readings. When a powerful magnetic field was switched on, directed along the plates and perpedicular to the drawing, the ionization in the electroscope chamber almost disappeared. This showed decisively that the α-ray was a current of charged particles which

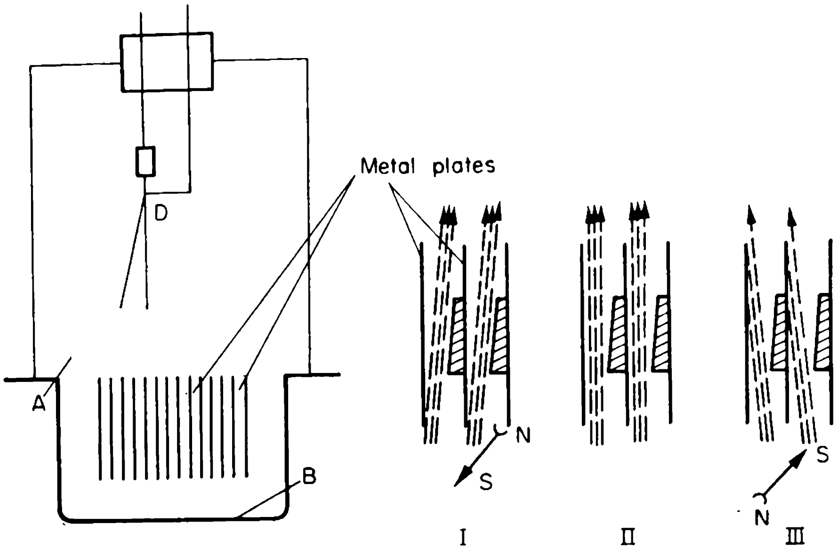


FIG. 1. Rutherford's determination of the nature of the α-particle. *A*—chamber, *B*—radioactive salt, *D*—electroscope. On the right: directions of stream of α-particles with changing direction of magnetic field.

were deflected on to the plates by the magnetic field. In order to determine the sign of the charge on the α-particles, part of the gap between the plates was obstructed. It then transpired that the readings of the electroscope depended on the direction of the magnetic field (towards the reader or away from the reader, Fig. 1, I and III). It is clear that when the stream of particles was deflected to the left a large fraction of the α-particles would fall on the plate. Hence, knowing the direction of the deflection of the α-rays by the magnetic field, it was not difficult to determine the sign of the charge on the α-particles, which turned out to be positive. Finally, by pro-

ducing an electric field between the plates, Rutherford also succeeded in producing a deflection of the α-particles for a definite value of the field.

The results of this experiment enabled Rutherford to determine the velocity of the α-particles, and also to find the ratio of their charge to their mass. It turned out that the α-particles were ions of helium carrying two positive charges, i.e. atoms of helium which had lost two electrons. Later on, when larger quantities of radium had become available (amounting to several grammes), Rutherford finally proved the correctness of his conclusions by the following experiment. A gas, formed of the α-particles which had passed through the very thin walls of a sealed glass tube containing radium emanation (radon), was collected for two days and two nights in the discharge tube A (Fig. 2). By raising the level of the mercury the gas was compressed and transferred to the capillary V. By passing an electric discharge through the capillary Rutherford was able to find in the spectrum of the radiation of the gas the characteristic yellow lines of helium.

The nature of the β-rays was also explained. They turned out to be very fast electrons moving almost with the velocity of light. There is also a third kind of radiation, called γ-rays, which are electro-magnetic waves of even shorter wavelength than the Röntgen rays.

Side by side with the study of radiations, the radioactive elements were also subjected to chemical investigation. It was shown, for example, that metallic radium formed in addition to helium a heavy radioactive gas (radon) similar in its properties to the inert gases neon and argon. Relying on these experimental facts, Rutherford and Soddy put forward, in 1903, a theory of radioactive decay. According to this theory, radioactivity is the spontaneous transformation of some elements into others. The atom, when it has expelled an α- or β-particle, is no longer an atom of the original element.

This discovery involved a fundamental revolution in science. The atoms, which had been regarded as the unshakable founda-

tion of matter, turned out to be unstable. From time to time they exploded, expelling particles which moved with enormous velocities, and changing into new atoms. A remarkable peculiarity of this radioactive decay was its complete independence

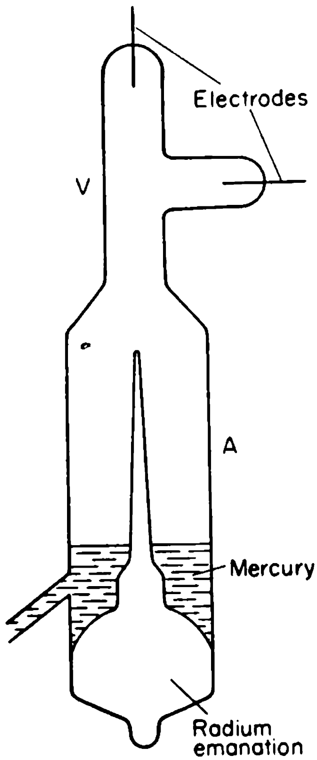


FIG. 2. Rutherford's experiment to prove the radioactive decay of the elements.

of external conditions: neither temperatures of 1000° nor high pressures were able to influence the rate of decay of a radioactive substance. The time in which half the original atoms decayed was called the half-life of the substance. It was impossible to take as a measure of the rate of decay of the nuclei the time in which all the nuclei of the radioactive element decayed. The observed law of decay (it is called an exponential law) is such that it would be necessary to wait an infinitely long time for the complete decay of any radioactive substance.

The rates of decay of the elements are very different: for some, the periods of decay are counted in thousands of years (for radium, 1600 years) and even in millions of years (for thorium 14 milliard years, for uranium 4·6 milliard years), while others decay almost instantaneously after millionth parts of a second. Three independent series of elements which are mutually transformed by radioactivity are known in nature (Fig. 3). In each of these, the successive decay of the elements takes place with the expulsion either of a α-particle or of a β-particle (an electron). In all the radioactive series—or families—the final stable non-decaying element is lead, or, more exactly, three of its different forms or isotopes.

The study of radioactivity has shown that substances exist which have identical chemical properties but differ in their half-lives and in the energy of the particles which are expelled. They were called isotopes, which means, in Greek, "occupying the same place", since all the isotopes of a given element are situated in the same square of the Mendeleyev table. It also became clear that isotopes of even stable elements existed. The nature of this phenomenon was made clear only after the discovery of the neutron. The elements found in nature are usually mixtures of several different isotopes. The final product of the uranium series, which begins with the uranium isotope of atomic weight 238, is lead of atomic weight 206. The thorium series ends in the isotope lead-208. Finally, the actinium series begins with uranium-235 and ends with the isotope lead-207.

"After the series of natural transformations of uranium and thorium had been studied, it was possible to hope that some day we should succeed in finding a way of breaking up the stable atoms of some ordinary elements. In order to attack this problem with any chance of success it was necessary to have some idea of the structure of the atom"—so wrote Rutherford later on.

The discovery of radioactivity led Rutherford to the idea of investigating the structure of atoms by bombarding them

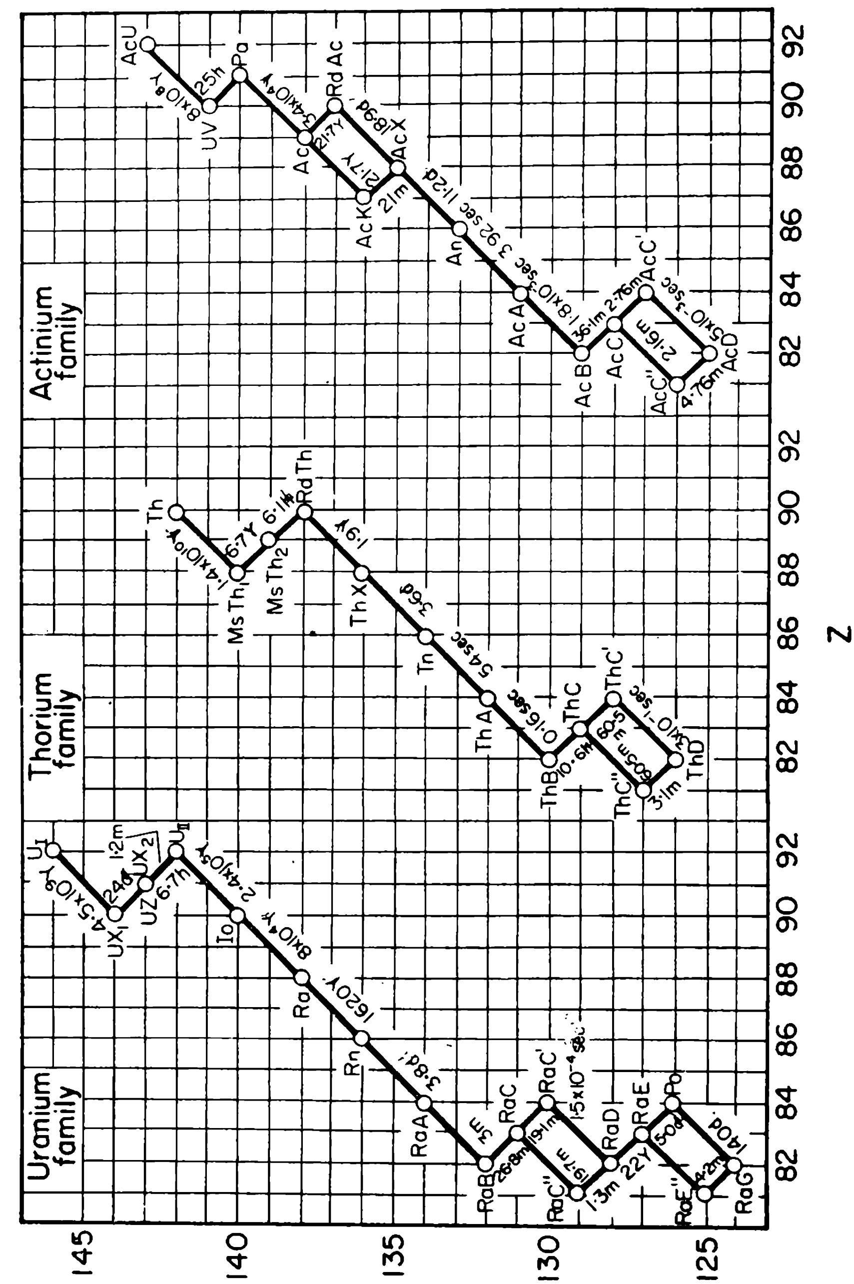


FIG. 3. Decay series of radioactive elements.

with α-particles from radium. He assumed that the investigation of the scattering of α-particles by individual atoms would give valuable information as to the nature and intensity of the deflecting field within the atom. But the observation of ionization by means of the electroscope did not enable him to fix the paths of individual particles. A new method of recording fast particles was found, also depending on the excitation and ionization of atoms. In studying the properties of rays physicists had noticed that certain substances shone (luminesced in the presence of radioactive matter. The microscopic observation of one of these substances when irradiated by α-particles showed conclusively that the continuous light seen by the naked eye was the sum of individual sparks (scintillations) arising, apparently, at the points which were struck by the α-particles. From these scintillations it was possible to determine the direction of the scattering of individual α-particles.

Having found a suitable way of observing the scattering of α-particles, Rutherford directed the young scientist Marsden, who had come to work in his laboratory, to observe how the direction of motion of the α-particles changed after passage through very thin sheets of gold foil. The experimental apparatus consisted of the radon source *R*, the α-particles from which passed through the diaphragm *D* and fell in a narrow beam on the thin foil *F* (Fig. 4). The α-particles scattered by the foil struck a screen covered with zinc sulphide. The scintillations produced on the screen *S* were observed in the microscope *M*. The microscope and screen could be rotated in the plane of the diagram round an axis passing through the point O perpendicularly to the sketch. For different angles the number of flashes appearing on the screen in a definite interval of time was counted. This is how this extraordinary experiment was carried out.

The observation of the scintillations was very hard work. The experimenter was obliged to accustom himself to the darkness for an hour and a half. Only after this time did his eye begin to perceive the flashes in the microscope. When they

were being counted a second experimenter sat in the next room recording the results. When it was necessary to make a change in the apparatus, the observer covered his eyes, the light in

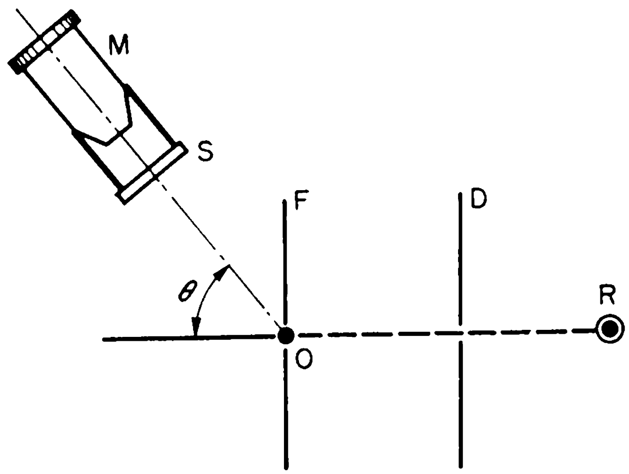


FIG. 4. Apparatus for observing the scattering of α-particles on gold.

R—source of particles, *D*—diaphragm, *F*—gold foil, *S*—scintilating screen, *M*—microscope.

the room was turned on, and the second experimenter came in, made the necessary adjustment, turned off the light, and then the measurements were continued. Nowadays, very sensitive photo-multipliers could replace the observer in the experiments described above.

What, then, were the results of Marsden's experiments, which he carried out in co-operation with Geiger? They appeared to confirm the conception of the atom put forward by Thomson. But although the overwhelming majority of the α-particles were deflected from their original direction through small angles of the order of 1°, as had been expected, very occasionally (in one case out of several thousands) deflection through very large angles of 90° or more were observed, so that a few α-particles were, so to speak, bounced back from the foil.

Many physicists knew of this unusual fact. But Rutherford alone appreciated its extraordinary importance. The experiments on the scattering of α-particles, in his opinion, indicated the existence of enormous forces within the atom. It was not known how these forces originated.

It is not difficult for us today to convince ourselves of the reasonableness of Rutherford's doubts. It is easy to show that on the Thomson model of the atom, we must exclude almost completely the possibility of large deflections of the α-particles. In the Thomson atom—a solid sphere of radius 10^{-8} cm with a uniform distribution of the positive and negative charges—there would be no forces capable of causing the α-particle to bounce backwards.

Let us consider an α-particle of mass M, with velocity v and a positive charge equal to $2e$, where e is the charge of the electron ($e = 4{\cdot}8 \times 10^{-10}$ CGSE). In the atom of gold on which the α-particle is scattered there are Z electrons and a positive charge Ze associated with practically the whole mass of the atom. Considerable deflection of the α-particle can be produced only by the action of the positive charge of the atom which is associated with high mass. If the distribution of the positive and negative charges is uniform, the value of the uncompensated positive charge must be approximately equal to e, and its linear dimensions must correspond to the mean distance between $R = 10^{-8}/Z^{1/3}$ cm. The angle of scattering of the α-particle, θ_1, is approximately equal to the ratio of the momentum communicated to the α-particle and the original momentum (equal to the product of its mass and velocity). On the other hand, the momentum communicated to the α-particle is equal to the force F acting upon it, multiplied by the time T of the action of the non-compensated charge:

$$\theta_1 \cong \frac{FT}{Mv}.$$

According to Coulomb's Law, the force of interaction is

$$F = \frac{2e.e}{R^2} = \frac{2e^2Z^{2/3}}{10^{-16}};$$

$$T = \frac{R}{v} = \frac{10^{-8}}{Z^{1/3}v}.$$

Hence $\theta_1 = 2e^2Z^{1/3} \times 10^8/Mv^2$ (in radians). If we substitute in this expression the value of $M=6 \cdot 6 \times 10^{-24}$ g, $v=10^9$ cm/sec and $Z = 79$ (for gold), then $\theta = 3 \cdot 0 \times 10^{-5}$ radians or $0 \cdot 0017°$.

In foil of the thickness of 5×10^{-5} cm, such as was used in the experiment, there will be about 3×10^{-18} atoms of gold per cm^2. Hence, knowing the cross-section of the atom $(\pi D^2/_4)$, we can find the number of collisions which the α-particle will experience. It will be equal on average to 230. From the theory of probablility it follows that with n random collisions the total deviation $\theta = \theta_1 \sqrt{n}$ or about $0 \cdot 02°$. The probability of a deviation through a larger angle amounting to several tens of degrees turns out to be completely negligible.

Thus the results of the experiments on the scattering of α-particles showed that the conception of the structure of the atom which prevailed at the time was erroneous. Rutherford based a new theory of the atom on the experimental facts. He put forward the bold hypothesis that the whole positive charge, and consequently almost the whole mass of the atom, was concentrated in a very small part of the atom at its centre. The radius of this part of the atom, which was called the nucleus, amounted to less than 10^{-12} cm, i.e. ten thousand times smaller than the dimensions of the whole atom.

The new model of the atom explained the appearance of α-particles flying in the reverse direction. These were the particles which passed very near to the nucleus and experienced the strongest force of repulsion from it. As is well known, the force of electrical interaction is inversely proportional to the square of the distance between the charges, and hence a near approach would increase the repulsive force by millions of times. A picture—though a very rough one—of the phenomena

of scattering can be given by the mechanical model represented in Fig. 5. In order that it may be deflected through a large angle, an α-particle must pass near to the nucleus, whose cross-section is a negligible part of the cross-section of the atom.

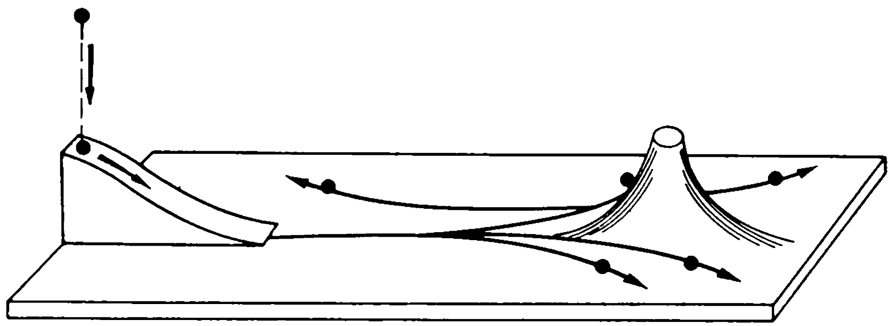


FIG. 5. Mechanical model of scattering of α-particles by the atomic nucleus.
Balls aimed exactly at the little hill are deflected through large angles. The others hardly change their direction.

If, in the example of the collision of α-particles with atoms of gold which is considered above, we replace the atom in the form of a sphere with uniform distribution of the charge by the Rutherford atom, we can find how near to the nucleus the α-particle must pass in order to be deflected through 90°.

For such a deflection the momentum communicated to the α-particle must be close to its own momentum Mv. Equating the communicated momentum as before to the product FT, where

$$F = \frac{2Ze^2}{R^2} \quad \text{and} \quad T = \frac{R}{v};$$

we have

$$R = \frac{2Ze^2}{Mv^2},$$

whence, after substituting the corresponding numerical values, we obtain $R = 5{\cdot}5 \times 10^{-12}$ cm. The radius of the nucleus must actually be less than this value. The probability of deflection through 90° will be found by taking the ratio of the sum of the areas πR^2 for all the atoms of gold contained in

1 cm² of the foil, to 1 cm²; the value 0·0003 obtained shows that out of 3000 α-particles only one will be deflected so strongly. This is approximately what is found by experiment.

Thus Rutherford's theory of scattering, in which he considered the electrostatic interaction of two point-charges, gave excellent quantitative agreement with experimental results. Moreover on the basis of this theory he later succeeded in determining directly the value of the nuclear charge from experiments on the scattering of α-particles. Within the limits of experimental error this coincided with the atomic number Z.

But where are the electrons situated in the atom? Rutherford assumed that they moved round the nucleus in circular orbits of various radii. Here the stability of the motion of the electrons is determined by the fact that the electrostatic attraction of the nucleus exactly compensated for the centrifugal force due to their rotation. This model of the atom very much resembles the solar planetary system, in which the planets are replaced by electrons and the sun by the nucleus. The difference, apart from the dimensions, lies in the nature of the forces acting in the system. In the atom the force is that of electrostatic attraction and in the solar system it is that of universal gravitation.

The planetary model of the atom was not at first accepted. The main objection to it was the inconsistency of the stable motion of the electron around the nucleus with the classical laws of electricity. An electron moving with acceleration round the nucleus must necessarily lose part of its energy in the form of radiation, as happens for example in a radio antenna or in a Röntgen tube. The loss of the energy of the electron in the atom must give rise to a reduction in its kinetic energy and its fall into the nucleus.*

* An electron moving uniformly in a circle round the nucleus undergoes acceleration, even though its speed does not change. The *direction* of its motion continually changes, and this change is produced by the force of attraction of the nucleus, and thus ranks as acceleration just as much as a change in its speed would do. [Translator]

In 1913 the Danish physicist N. Bohr came out in defence of the planetary model of the atom. He put forward the brilliant idea of the existence of stationary stable conditions in the atom in which the electron does not radiate energy. Each of these states is characterized by a strictly defined energy, and the radiation and absorption of energy in the form of light takes place only when the atom passes from one state to another. This transition corresponds to the jump of an electron from one level to another.

In his theory Bohr made use of the conception of the discrete nature of energy in the micro-world. At the beginning of the twentieth century Planck showed that light of a definite wave-length cannot be given out or absorbed in any small quantity we please, that in fact there exists a minimum quantity of energy—the so-called quantum. The correctness of this extremely important discovery was soon confirmed by the study of the photo effect, i.e. the phenomenon of the expulsion of electrons on the absorption of light by the atoms. Thus in

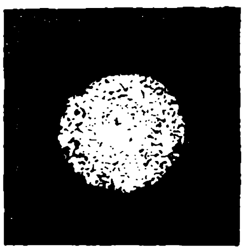


FIG. 6. Distribution of electric charge in the hydrogen atom. Fundamental state.

some experiments, as, for example, in diffraction, the wave nature of light was revealed, and in others the quantum nature. In the latter experiments light behaved like a stream of rectilinearly propagated particles. Later on it became clear that a similar duality of nature also existed in the case of particles, e.g. electrons. These discoveries formed the basis for the creation of a quantum-mechanical theory.

The new theory showed that Bohr's conception of the existence of electronic orbits in the atom was incorrect. It turned out that such conceptions as orbit and trajectory were generally inapplicable to the electron in the atom. Quantum mechanics show that all that could be defined was the probability of finding an electron at a particular point in the atom. This probability characterized the distribution of electric

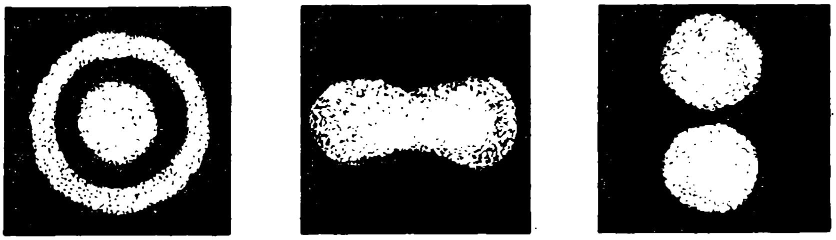


FIG. 7. Distribution of electric charge in the hydrogen atom. First excited states.

charge in the atom or the distribution of the electron cloud around the nucleus. Figures 6 and 7 show the distribution of the electric charge calculated theoretically for the hydrogen atom in its different states.

2. BOMBARDING THE NUCLEUS

As we have seen, the clarification of Rutherford's first model of the atomic structure was concerned with the electrons. The fundamental idea of the existence within the atom of a nucleus of relatively negligible dimensions has endured the test of time. Making use of these ideas on the atomic structure, Rutherford set out to bring about the artificial transformation of the elements. The study of natural radioactivity had already shown that enormous reserves of energy were imprisoned within the centre of the atom—since otherwise the particles expelled by the atom would not possess such enormous velocities. After the discovery of the atomic nucleus it became obvious that this energy was actually concentrated there. Hence it was quite clear why the innumerable experiments of the alchemists, who

for a number of centuries tried to transform different metals into gold by means of chemical reactions or mechanical action, were unsuccessful.

By chemical methods or by means of electric discharges it was not difficult to unite several atoms or at times to tear out of the atom the external electrons. However, another electron soon occupied the vacant place, and the atom returned to its former state. The stable transformation of an element can be carried out only by acting on its nucleus in such a way as to change the composition of the nucleus.

But how was it possible to act on the nucleus? Thanks to the action of the enormous intranuclear forces, the mass of the nucleus possessed fantastic density—one cubic centimetre completely filled with atomic nuclei, would weigh about one hundred million tons!

It was clear to Rutherford from the very outset that in order to split the nucleus very powerful sources of energy would be required. The greatest energy available at the time was that possessed by the α-particles of radium or other radioactive substances. It was decided to try to realize the transformation of atomic nuclei by bombarding them with α-particles. These were the same missiles which had been used earlier for the study of the atomic structure. But in this case their task was entirely different.

In order to transmute the nucleus it was not sufficient for the nuclear missile to pass near to it. It was necessary that it should hit the nucleus directly. Knowing the character of the forces acting between the α-particles and the nucleus (up to their very close approach these forces were those of electrostatic repulsion), it was not difficult to determine whether the energy of the α-particle was sufficient to overcome these forces and reach the nucleus. The distance of nearest approach of an α-particle to a nucleus with charge Ze can be found by equating the kinetic energy of the α-particle to the energy of repulsion

$$\frac{Mv^2}{2} = \frac{2eZe}{R},$$

whence

$$R = \frac{4Ze^2}{Mv^2}.$$

If we substitute in this formula $Z = 79$ (for gold) and the velocity of the α-particle, $v = 1 \cdot 7 \times 10^9$ cm/sec, then we see that $R = 3 \cdot 8 \times 10^{-12}$ cm. That is, we find that an α-particle is not able to "penetrate" the nucleus of a heavy element such as gold, since its radius is less than 10^{-12} cm. Let us consider whether the α-particle can approach the nucleus of the light element nitrogen with frontal attack. Substituting the charge

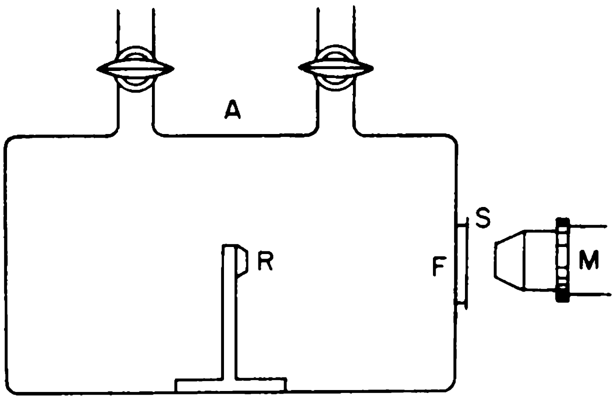


FIG. 8. Diagram of first experiment on the artificial splitting of the atomic nucleus.
R—radioactive source, *S*—screen, *M*—microscope, *F*—silver foil.

of the nitrogen nucleus, $Z = 7$, we find $R = 3 \cdot 3 \times 10^{-13}$ cm, which is approximately equal to the radius of the atomic nucleus of nitrogen.

On the basis of these considerations Rutherford, in 1919, undertook new experiments which led to one of the most outstanding discoveries of the present century—the realization of the artificial transmutation of the atomic nucleus.

The apparatus constructed for this purpose was very simple (Fig. 8). The air-tight chamber *A* was filled with well-dried pure nitrogen. In the centre of the chamber the radioactive

source R was placed as the source of α-particles. An opening in the side wall of the chamber was covered by a leaf of silver foil F, thick enough to absorb the α-particles. Beyond this leaf there was a screen of zinc sulphide S and a microscope M for observing the scintillations.

As the chamber was filled with gas, the greater part of the scintillations produced by the α-particles disappeared, but a very small number remained although it was known that the α-particles could not penetrate through the gas and the silver screen owing to the loss of energy in ionization. The replacement of the nitrogen in the chamber by oxygen or carbonic acid gas produced a complete cessation of the scintillations.

Rutherford assumed that the remaining scintillations in the case of nitrogen were due to particles of high energy which were expelled by the nitrogen nucleus under the action of the α-particles. In order to determine the nature of these particles, and their mass, the chamber was placed in the field of an electro-magnet. The numbers of scintillations in a definite interval of time were compared when the poles of the magnet were reversed. The same operation was carried out when, instead of nitrogen, the chamber was filled with a mixture of hydrogen and carbonic acid gas. In this case the scintillations were produced by hydrogen nuclei—protons—which on collision with α-particles acquired a recoil energy similar to that of a billiard ball when struck by another ball. The ratio of the number of scintillations on the reversal of the magnetic pole was the same as in the experiment with nitrogen. "Thus," wrote Rutherford, "it was clear that some nitrogen atoms had been disrupted by collision with swift α-particles and that fast atoms of positively charged hydrogen resulted... Hence we must conclude that the charged atom of hydrogen is one of the components of the nitrogen nucleus."

What, then, happened to the nitrogen nucleus into which an α-particle penetrated as the result of a successful collision? Experiment showed that the nucleus expelled a proton. Since in the process of nuclear transmutation the total electric charge

must be conserved, it is not difficult to show that from the nitrogen nucleus a nucleus of the neighbouring element, oxygen, will be formed (Fig. 9). Thus the first artificial nuclear reaction was produced. It would not be correct, however, to call this

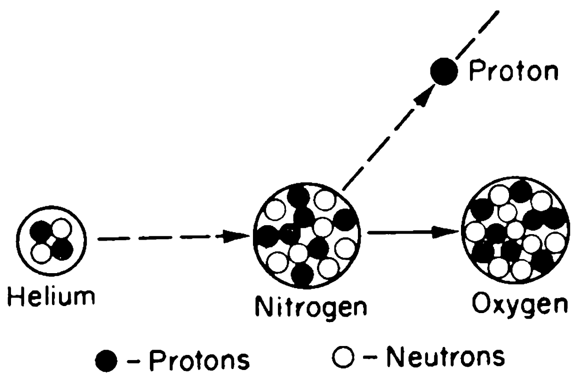


FIG. 9. First nuclear reaction carried out by man.

the splitting of the nucleus, since the result of this reaction is the formation of the nucleus of a more complicated element than the original.

There is a very graphic way of observing suitable nuclear transformations. In spite of the fact that the nuclei and the particles themselves cannot be seen, many details of the process have been successfully observed. We already know that in passing through any substance a charged particle loses energy, leaving in its wake charged ions. If we compel a fast particle to pass through a space full of super-saturated vapour, then drops of water will condense on the ions. These drops, which are visible to the naked eye, indicate the path of the invisible particle. The trace of the particle, consisting of drops of water, remains for a long time and can be photographed on a film. An apparatus based on this principle is called the "Wilson Chamber" and is widely used in nuclear research. It was also used for studying the first nuclear reactions.

Figure 10 shows a photograph obtained in the Wilson Chamber in the process of the transmutation of the nucleus of ni-

trogen into a nucleus of oxygen under the action of α-particles. The straight thick traces belong to the α-particles passing from below upwards into the chamber like a fan, the chamber being filled with nitrogen. We see that in one place the trace divides. Here a nuclear reaction has taken place. The short thick trace

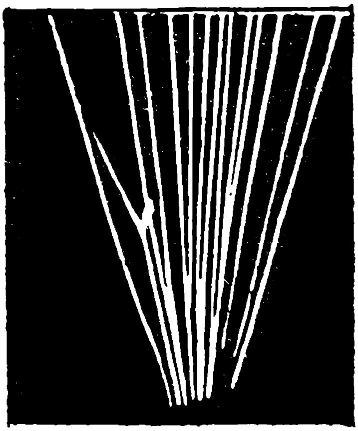


FIG. 10. Splitting of nitrogen atom under the action of α-particles. The thin trace on the left belongs to a proton, the thick trace to the oxygen nucleus formed.

belongs to the oxygen nucleus. The thinner and longer trace is left by the proton. By measuring the lengths of the traces of the particles as they fly apart we can find their velocity and their energy.

It would be difficult to exaggerate the importance of the discovery of a method of artificially transforming atomic nuclei. Even the first nuclear reaction gave extraordinarily interesting information about the composition of the nucleus—one of the particles composing the atomic nucleus, the proton, was discovered. The other component of the nucleus—the neutron—was observed later in 1932. During the following ten years, various nuclear transformations were achieved, and enriched science with new discoveries.

CHAPTER II

THE SECRETS OF MATTER WILL BE REVEALED

3. THE FIRST ACCELERATORS

In spite of the remarkable success of the first attempts to transmute atomic nuclei, formidable obstacles to the further development of this branch of physics were found to exist. Bombardment with α-particles could effect the transmutation of the nuclei of only the very lightest elements. Even the velocity of the fastest α-particles expelled by radioactive elements—amounting to about 19,000 km/sec—proved insufficient to overcome the forces of electrostatic repulsion exerted by the majority of nuclei. At the surface of a heavy nucleus the α-particle, whose mass was only $6 \cdot 6 \times 10^{-24}$ g, was repelled with a force of 100 kg. The nucleus was surrounded by a strong protective barrier. In order to penetrate it, missiles of greater power than the α-particles of natural radioactive sources were required.

Another shortcoming of the first weapons of atomic artillery was their low "rate of fire". The currents of α-particles expelled by the sources proved to be insufficiently intense. The fact was that nuclear breakdown was a rare phenomenon. In order to obtain the photograph of the nuclear transmutation of nitrogen shown in Fig. 10 it was necessary to photograph one hundred thousand tracks of α-particles! And this is not surprising. For the atom is practically empty, since the nucleus occupies a negligible part of its volume. In the bombardment of targets by nuclear missiles, the greater part of them pass through the atom without touching the nucleus.

Let us try to estimate roughly the probability of a direct hit by an α-particle on a nucleus. Let the target subject to bombardment have the form of a square with a 1 cm side perpendicular to the direction of flight of the α-particles. If the target contained only a single atom of matter, the probability σ of a hit would be determined by the ratio

$$\sigma = \frac{\pi R^2 \text{cm}^2}{1 \text{ cm}^2}$$

where R is the radius of the nucleus (about 3×10^{-13} cm). Then $\sigma \approx 10^{-25}$. It might seem that by taking a target of sufficient thickness, containing a large number of atoms per area of 1 cm^2, we could compel each α-particle to collide with a nucleus. But this argument neglects one important circumstance: the passage through an atom is not without its effect on the α-particles. They lose part of their energy in exciting or ionizing the atom. In order to retain an energy sufficient for nuclear transformation, an α-particle must pass through a target of thickness not greater than 1μ.* With this thickness there are approximately $N = 10^{19}$ nuclei per cm^2. Hence the total probability $W = \sigma N = 10^{-6}$, that is, out of a million α-particles, only one will strike a nucleus.

Thus, the insufficient energy of the α-particles and the low intensity of natural radioactive sources slowed down the development of nuclear physics. New and more powerful missiles were required. But how were they to be obtained? Was it possible to speed up artificially to greater velocities the nuclei of light elements, for example hydrogen, and to use them for the bombardment? It turned out that this could actually be achieved by the use of the well-known fact that charged particles were accelerated under the action of an electric field.

Suppose that a great potential difference is established between the plates A and B (Fig. 11). A positively charged particle in the neighbourhood of the plate A would move under

* $1\mu = 10^{-3}$ mm [Translator]

the influence of the electric field towards the negatively charged plate *B*, and would actually reach it, if a vacuum was created in the space between *A* and *B*. During its movements from *A* to *B* the particle would acquire a quite definite kinetic energy. It is the custom in atomic physics to measure energy in terms

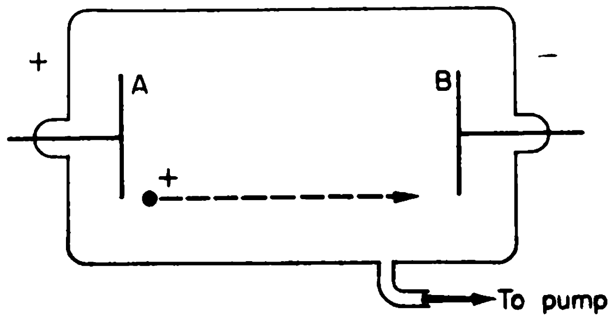


FIG. 11. Principle of acceleration of charged particles.

of a special unit—the electron volt. An energy of one electron volt (eV) is acquired by a particle with unit electric charge (e.g. a proton or an electron) in passing through a potential difference of 1 V.*

If a potential difference of 1000 V is established between the electrodes *A* and *B*, then in passing from one electrode to another a proton will acquire an energy of 1000 eV or 1-kilo-electron volt (keV).

If the charge on the particle which is being speeded up is equal to two elementary charges (e.g. in the case of the doubly-ionized atom of helium—the α-particle), then the energy acquired by it will also be correspondingly twice as great as the energy obtained by a singly-charged particle. An energy of 1 eV is not very great; it is equal only to $1 \cdot 6 \times 10^{-12}$ ergs.

* In the rest of this book we shall make use of the following generally accepted abbreviations:

1 keV = 1000 electron volts;

1 MeV = 1,000,000 electron volts;

1 BeV = 1,000,000,000 electron volts.

However, it is sufficient to communicate to an atom an energy of a few electron volts, in order to tear off one of its external electrons. Nuclear transformations involve the expenditure of energies millions of times greater. The fastest α-particles expelled by radioactive nuclei have an energy not exceeding 10 MeV.

Thus, to obtain particles of greater energy it is necessary to place their sources in a very strong electric field. This was the method followed by the inventors of accelerators—apparatus for obtaining charged particles of high velocity.

The first accelerators consisted of two principal parts—an apparatus for obtaining a high voltage and a high voltage vacuum tube, within which the acceleration of the particles took place. The vacuum tube was constructed of material with good insulating properties—glass, porcelain, or ceramic. It had to withstand a voltage of several million volts applied to the electrodes situated at each end. The air is pumped out of the vacuum tube. The residue which remains in the tube is approximately a milliard times less than before pumping out. This high rarefaction considerably reduces the probability of the collision of an accelerated ion with a gas molecule, and also improves the insulating properties of the apparatus.

The achievement of a good vacuum is an important problem in the construction of any accelerator. The exhausting of the air is carried out in two stages. First of all mechanical centrifugal pumps produce a rarefaction of about 10^{-2}–10^{-3} mm of mercury. Then so-called diffusion oil pumps come into action and ensure the necessary vacuum (10^{-5}–10^{-6} mm of mercury). The attainment of such a high vacuum naturally requires good air-tight joints, apparatus for registering the state of the vacuum and other measures, on which we cannot linger here.

In the case of the acceleration of positively charged particles the source of ions (Fig. 12) is placed near the positive electrode. The ions are obtained by bombarding the atoms of a gaseous element (e.g. hydrogen in the case of the acceleration of protons, or helium for the acceleration of α-particles) with elec-

trons, given off by a heated metallic wire. The ions thus formed are removed from the source by the electric field.

In addition to the two principal electrodes, to which a high voltage is communicated, the vacuum tube contains a number of intermediate electrodes. By means of a potential divider,

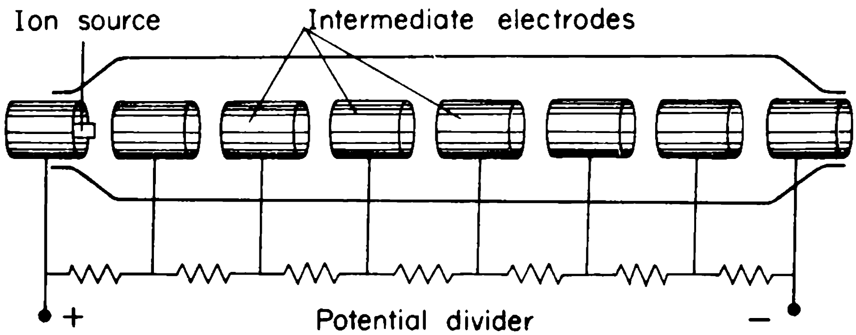


FIG. 12. Diagram of construction of vacuum tube.

each of the intermediate electrodes receives a definite fraction of the total voltage. The intermediate electrodes render the fall of potential along the axis of the tube more uniform and prevent the appearance of discharges at its end. But this does not exhaust the role of the intermediate electrodes. They solve one more extremely important problem.

The vacuum tube in which the ions are accelerated has a length of several metres. Is it possible to be sure that all or at least most of the particles expelled by the source will succeed in traversing the whole length of the tube whatever its construction may be? Unfortunately it is not. Obstacles which happen to be in the path of the ions—molecules of gas remaining in the accelerator—will change their directions. Moreover, since they have the same charge, the ions will repel one another. It is important to remember that the particles from any source form a somewhat diverging beam. All these causes make it necessary to take special measures to render the beam convergent or, in other words, to focus the particles in accelerators.

In the vacuum tube described above, the focusing of the particles takes place in the spaces between the intermediate

electrodes. The lines of force of the electric field are directed in the left-hand half of the gap towards the axis of the tube, and in the right-hand half of the gap away from the axis (Fig. 13). This means that a beam of positive ions moving from left to right is first converged towards the axis, that is,

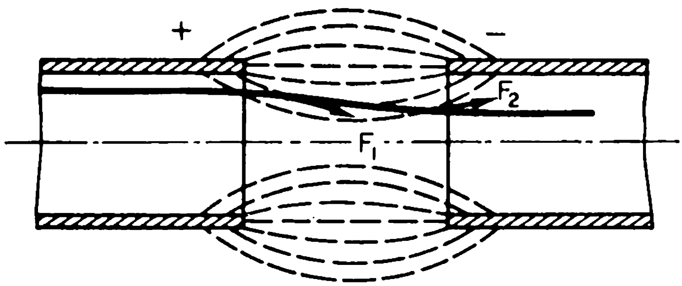


FIG. 13. Focusing action of accelerating gap.

focused, and then in the second half of the gap is bent away from the axis towards the sides. It might seem that on the whole the gap between the intermediate electrodes would not focus the ionic beam. However, this is not the case. As they move within the electrodes the particles do not experience the action of an electric field, and consequently are not accelerated. The increase in velocity takes place only during the time when they traverse the gap. They traverse the left-hand focusing half of the gap more slowly than the right-hand de-focusing half. Hence, on the whole, the beam is focused by the gap.

We have considered the construction of one of the elements of the high voltage accelerator—the vacuum tube. The necessary high voltage for the acceleration of the particles has to be applied to the tube. It can be obtained in several ways. In the so-called cascade generator, a condenser is charged in each section, by means of a high voltage transformer and a rectifying valve—the kenotron (Fig. 14). The potential of the upper plate of the outermost condenser with respect to the earth will be equal to the sum of the voltages of all the condensers.

In 1932 the English physicists Cockroft and Walton accelerated protons by means of a cascade generator to an energy

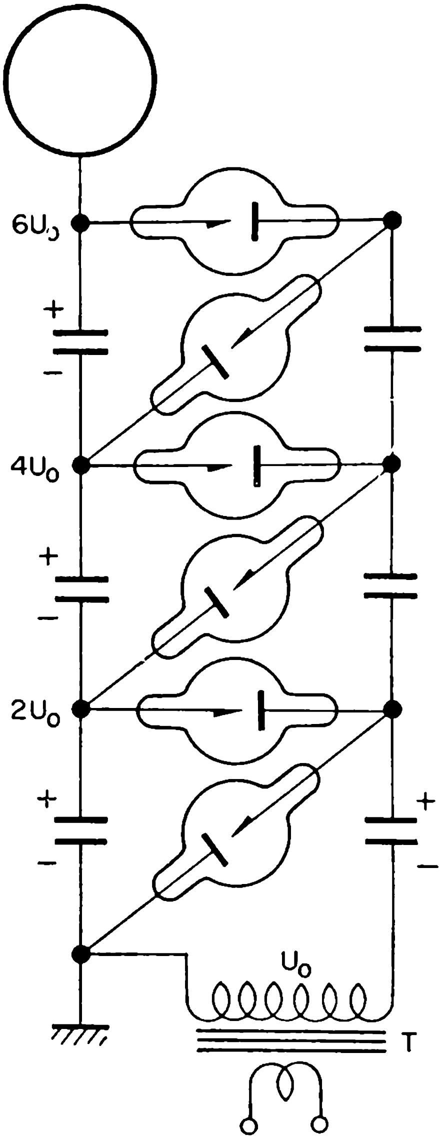


FIG. 14. Illustration of principle of cascade generator.

of 700 keV and were the first in history to achieve a nuclear reaction produced by artificially accelerated particles. As a

result of this reaction the lithium nucleus which formed the target was transformed into two fast α-particles (Fig. 15).

This experiment showed that α-particles were not the only ones which could be used as missiles in the bombardment of

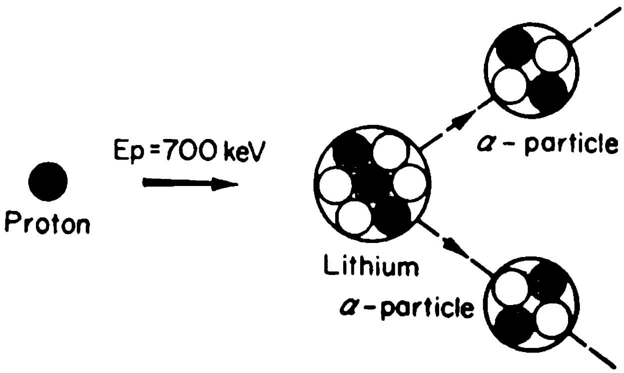


FIG. 15. First nuclear reaction produced by means of an accelerator.

atomic nuclei. Moreover it became clear that protons could produce a given nuclear reaction when they possessed an energy of only several hundred keV, whilst for α-particles from natural radioactive sources an energy of several MeV was required. This greater effectiveness of protons in comparison with α-particles was partly due to the fact that the proton, with a charge twice less than the α-particle, could more easily approach the target nucleus. The principal reason, however, was that even in the first accelerators beams of ions were obtained whose intensity exceeded by hundreds or thousands of times the intensity of the most powerful radioactive natural sources. Thus, in spite of the very low probability of the splitting of a nucleus (out of 100 million protons with an energy of 200 keV falling on the lithium target, only one proton produces the transformation of the lithium nucleus into two α-particles), the observation of this process became much easier than in Rutherford's first experiments. At the present time, cascade generators are used for obtaining intense beams of fast neutrons (up to 10^{11} particles per sec).

Another high voltage generator which has been widely used was constructed by Van-de-Graaf. In its construction this apparatus resembles the electric machine now used for experi-

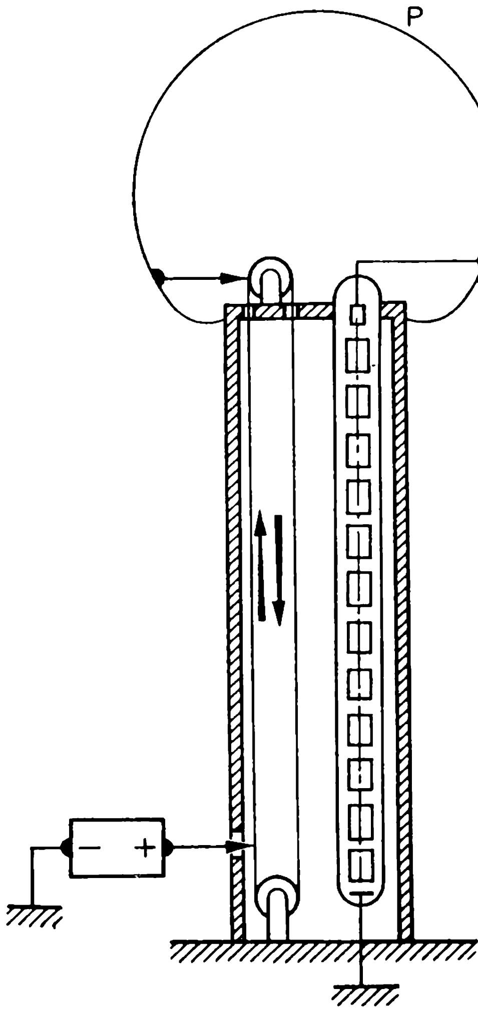


FIG. 16. Van-de-Graaf electrostatic generator.

ments in schools. The external appearance of the first electrostatic generators was very unusual (Fig. 16). The huge empty metallic sphere P was insulated from the earth by means of a tall column. An electric charge gradually accumulated on the surface of the sphere. It was delivered to the internal sur-

face of the sphere by means of an endless ribbon of paper or silk. The charge was delivered to the swiftly moving ribbon through a special comb, and in the same way was taken from the ribbon and flowed over the surface of the sphere. The potential of the sphere increases until further increase is prevented by leakage through the air and over the surface of the insulators.

One of the most powerful electrostatic generators, constructed at Kharkov in 1937, had a sphere with a diameter of about 10 m. A voltage of from 4 to 5 million volts was delivered to the 10 m long vacuum tube in which the particles were accelerated. In recent years the dimensions of electrostatic generators have been considerably reduced. This was successfully achieved by placing the whole accelerator in an atmosphere of compressed gas (nitrogen or freon*). A pressure of several atmospheres increased the stability of the apparatus against electrical breakdown.

Van-de-Graaf accelerators are widely used in nuclear research. They have recently found another application in the construction of the newest accelerators, in which they are used for the preliminary acceleration of the ions.

4. THE NEUTRON—AN UNUSUAL MISSILE

At the time when the first attempts at the artificial production of fast particles—missiles for splitting atomic nuclei—were being made with high voltage accelerators, physicists working with natural sources of α-particles discovered a new missile for the atomic artillery, and perhaps the most remarkable of them all.

The foundation was laid by the German physicists Bothe and Becker. Studying the results of the bombardment of different nuclei by α-particles from polonium, they chanced upon a phenomenon which they did not understand: the light metal beryllium, under the action of the α-particles, gave out some

* Chloro-fluoro-methane, a gas used as a refrigerant.

kind of unusual radiation which was capable of passing through considerable thicknesses of matter almost without absorption. It was obvious that the new radiation could not be attributed either to β-rays, which could not penetrate more than a few millimetres of solid matter, nor, still less, to α-rays which could not even penetrate a thin sheet of paper.

It might be that in the course of the nuclear reaction on beryllium γ-rays were formed. Experiments carried out by the Joliot-Curies (husband and wife) showed that this hypothesis was also not very probable. They placed paraffin wax, which contains, as is well known, a large number of hydrogen atoms, in the path of the mysterious radiation. As a result swift protons were expelled from the paraffin with an energy of several MeV. A simple calculation showed that to communicate to the protons such a considerable energy, γ-rays with an energy of several tens of MeV would be required, which is much greater than the energy of the original α-particles.

The secret of the new phenomenon was unravelled in 1932 by the English physicist Chadwick. He showed that the "beryllium" radiation consisted of a current of neutral, i.e. electrically uncharged, particles—neutrons—approximating in mass to the proton.*

In the same laboratory where Chadwick made his discovery, twelve years before, Rutherford had searched for a neutral particle which he believed must exist in nature. However, at that time the neutron was not discovered.

The discovery of the neutron rendered it possible to make the representation of the structure of the nucleus more precise. It turned out that the neutron, along with the proton, was a component part of all atomic nuclei (this was first proposed by the Soviet physicist D. D. Ivanenko and the German physicist V. Heisenberg). If the charge on the nucleus, equal to the number of the element in the Mendeleyev periodic system,

* The mass of the neutron is greater than that of the proton by $0 \cdot 0025 \times 10^{-24}$ g.

depends only on the number of protons in it, the mass of the nucleus, and consequently its atomic weight (A), is determined by the total number of protons and neutrons in it. For example, the familiar α-particle consists of two protons ($Z = 2$) and two neutrons ($A = 4$). Now, after the discovery of the neutron, the nature of isotopes became clear. They are distinguished from one another only by the number of neutrons they contain. Thus, for example, hydrogen has three isotopes. In the nucleus of the most common isotope H^1 there is one proton. The nucleus of the second isotope of hydrogen—deuterium—consists of a proton and a neutron (this isotope is very rarely met with, its distribution is 0·015 per cent). There is also a third isotope—tritium—H^3 which is obtained artificially. Its nucleus contains, besides a proton, two neutrons. There are elements found in nature which have a large number of stable isotopes. Tin, for example, possesses ten.

Shortly after the discovery of the neutron, investigators of nuclear transmutations achieved one more great success. The new missiles were our old friends the α-particles expelled by radioactive elements. Irene and Frederick Joliot-Curie in France observed that targets of boron, aluminium and magnesium, after bombardment with α-particles, became radioactive. Up to that time it had been supposed that, as a result of artificial nuclear transmutations, fast particles and stable atomic nuclei were formed. It was assumed that radioactivity was the property only of certain heavy elements. The Joliot-Curies discovered nuclear transformations which led to the formation of unstable radioactive isotopes of various elements. With the nucleus of the element boron, for example, we could have the reaction*

$$ {}_5B^{10} + {}_2He^4 = {}_7N^{13} + {}_0n^1. $$

* The subscript figures on the left denote the number of protons, and the superscript figures on the right the total number of protons and neutrons in the nucleus.

The isotopes of nitrogen $_7N^{13}$, as distinct from the stable isotope $_7N^{14}$ found in nature, is unstable and decays with a half-life of about 10 min, being transformed into the stable isotope of carbon $_6C^{13}$

$$_7N^{13} \rightarrow {}_6C^{13} + {}_1e^0.$$

In these experiments a new form of radioactivity was discovered, which expelled a positively charged particle—the positron $_1e^0$. This particle, with a mass equal to that of the electron, had been observed a short time earlier in cosmic rays, a stream of particles falling on the earth from inter-stellar space.

The discovery of artificial radioactivity played an enormous part in the development of our ideas of the nucleus. Subsequently, when it became possible to obtain considerable numbers of radioactive isotopes by means of nuclear reactions, they came to be applied in different realms of science and technology. At the present time about 1100 radioactive isotopes have been discovered, a considerable proportion of them being obtained under the action of neutrons.

The enormous penetrating power of neutrons, their power of "not noticing" the atoms of matter through which they pass, can be explained by the absence of electric charges in them. The neutron does not inter-act with the electrons of the atoms, and consequently does not lose energy by ionization. Direct collision with nuclei occurs very rarely, owing to the relative dimensions of the nucleus. Moreover, even collision with nuclei rarely leads to loss of energy by the neutron. On striking any nucleus, the neutron bounces back with almost the same velocity which it possessed before the collision. Here the picture very much resembles phenomena which occur with ordinary large bodies. A billiard ball bounces back from the cushion of the table without losing its velocity and only changes its direction. On the other hand, on striking another ball, the first ball loses, on the average, half of its velocity. In the same way fast neutrons communicate part of their energy to the hydrogen nuclei

contained in paraffin. Hence, in order to slow down neutrons, we use not dense, heavy substances, but light substances containing hydrogen, such as water, paraffin and cement.

The absence of an electric charge in the neutron ensures its free approach to any atomic nucleus. For the neutron there is no barrier round the nucleus. Naturally, physicists at once began to make use of the new weapon in their attacks on the atomic nucleus.

However, the first investigations of nuclear transformations produced by neutrons led to unexpected and very interesting

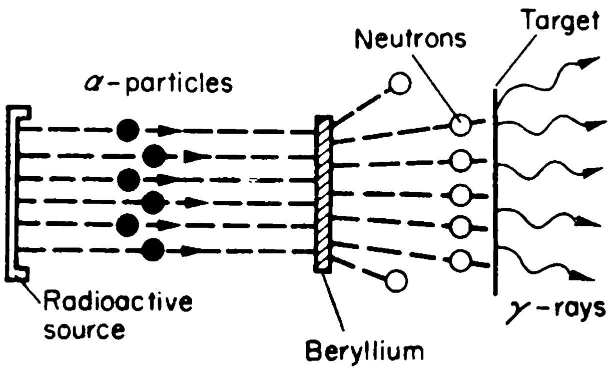


FIG. 17. Reaction under influence of neutrons.

results. In these researches, which were first carried out by the Italian physicist Enrico Fermi and his collaborators, the neutrons were obtained by the irradiation of beryllium with α-particles from a radioactive source. It was as though double splitting occurred (Fig. 17). On encountering the beryllium nucleus, the α-particles knocked a neutron out of it, which, in its turn, was absorbed by one of the nuclei of the target.

In the first place it appeared that under the action of neutrons the nuclei of almost all the elements of the periodic system passed into a radioactive condition. The new nucleus, formed on the absorption of the neutron, became radioactive.

In the second place, the radioactivity of the bombarded target strongly increased when the source of neutrons or the

substance of the target itself was surrounded by water or paraffin. We know that this meant a reduction in the speed of the neutron. It remained only to make the striking discovery that the slower the neutron the greater the probability that it would be absorbed by the nucleus, and the more often nuclear transformation would occur. In the case of certain substances the absorption of neutrons is especially strong. Thus a sheet of cadmium metal as thin as cigarette paper proved to be a stronger absorber than several centimetres of lead.

We perceive that neutrons as nuclear missiles possess remarkable properties, quite unlike the properties of α-particles and protons. The less their velocity, the greater the effects they produce. This is to be explained by the fact that the neutron, as distinct from the charged particles, has no need to overcome the forces of repulsion of the electrical field of the nucleus. Hence it does not need velocity. On the contrary, the more slowly it moves, the longer the time in which it is in the neighbourhood of the nucleus and the more likely it is to be captured by the nucleus.

Nuclear reactions which take place with the absorption of slow neutrons cannot be called nuclear splitting. As a result the nucleus does not split, but becomes more complicated, since one more neutron is added to it. However, the nucleus expels one or several γ-quanta. These γ-quanta are particles of light just as real as other elementary particles. The special feature of the γ-quanta is that their rest mass is equal to zero and they always move in a vacuum (independently of their energy) with the velocity of light.

What then happens to the nucleus in nuclear transformations? Is there a difference between nuclear reactions and the collision of fast particles with atoms? The answer to these questions was given in 1936 by the Danish physicist Niels Bohr. He proposed the following simple model to explain nuclear reactions and the properties of the nucleus. Imagine a shallow bowl in which there are several billiard balls (Fig. 18). Let a single billiard ball be projected into the bowl. The ball, when

it falls into an empty bowl, rolls to the bottom and then jumps out at the other side. But there are already other billiards balls in the bowl. The ball which has been projected from outside will inevitably collide with them and communicate to them part of its energy. Let the bowl and the balls be completely smooth and elastic. In this case the collisions between

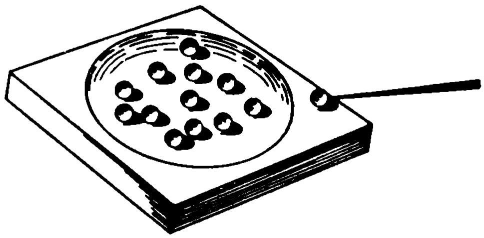


FIG. 18. Illustration of course of a nuclear reaction on Bohr's model.

the balls will continue until all the kinetic energy is concentrated in a single ball in the neighbourhood of the surface, after which this ball will leave the bowl.

Something similar takes place in the atomic nucleus during a nuclear reaction. The protons and neutrons of the nucleus, according to Bohr's model, are analogous to the billiard balls. The particle which penetrates the nucleus remains there, its energy being redistributed among all the nucleons of the nucleus.*

A complex system is formed, the so-called "compound nucleus". The duration of the existence of the compound nucleus exceeds by millions of times the time ($\sim 10^{-21}$ sec) which would be required for the particle to pass through the nucleus. Thus, according to Bohr's model, the nucleus is an opaque sphere which "absorbs" any missile which strikes it. As a result of the absorption of the energy of the missile an "excited" nucleus is formed which passes into a restful, unexcited state by means of the expulsion of particles or γ-quanta.

* Nucleon is a general name for the protons and neutrons which enter into the composition of the nucleus.

A very important property of nuclei is their power of acquiring only quite definite quantities of energy in the excited state. This is one of the properties of micro-particles which distinguish them from visible objects.

Bohr's model of the nucleus played an important part in explaining the properties of atomic nuclei. However, the experiments of recent years have shown that a particle which hits the nucleus is by no means always absorbed by it. Sometimes this particle can pass right through the nucleus, with practically no loss of energy. At high energies of the bombarding particles several particles may fly out of the nucleus, in which case in addition to protons, neutrons and α-particles, there may also be heavier particles expelled.

In considering nuclear reactions which take place under the influence of neutrons, it is impossible not to mention the process of nuclear fission. This process was discovered in the course of experiments aimed at obtaining artificially a new element with a greater number of protons than uranium ($Z = 92$). Atoms of uranium irradiated by slow neutrons actually exhibited radioactivity which, in its properties, was not similar either to that of uranium or to that of the neighbouring elements. After several years of experiment physicists were led in 1939 to an astonishing discovery. The radioactivity which had been discovered belonged not to a trans-uranic element but to two elements situated in the middle of the periodic table of Mendeleyev. Thus a new type of nuclear reaction was observed—the fission of heavy nuclei. It might appear that the breaking up of the uranium nucleus into two approximately equal parts was possible only when a very large quantity of energy was communicated to it. However, this is not the case. The fact is that in a heavy nucleus the forces of repulsion between the protons are extremely great. So long as the nucleus has a form close to spherical, the nuclear forces which act between the nucleons are in equilibrium with the forces of repulsion. However, if under the action of an absorbed neutron the nucleus is obliged to change its form somewhat (Fig. 19), then the

forces of repulsion tear the nucleus apart into two fragments which fly asunder in opposite directions with great velocity. There exists, it is true, a very low probability of the spontaneous fission of the uranium nucleus (half-life $\approx 8 \times 10^{15}$ years). This phenomenon was discovered in 1939 by the Soviet physicists K. A. Petrzhak and G. N. Flerov.

The discovery of the reaction of the fission of heavy nuclei played a decisive part in the practical use of the energy locked

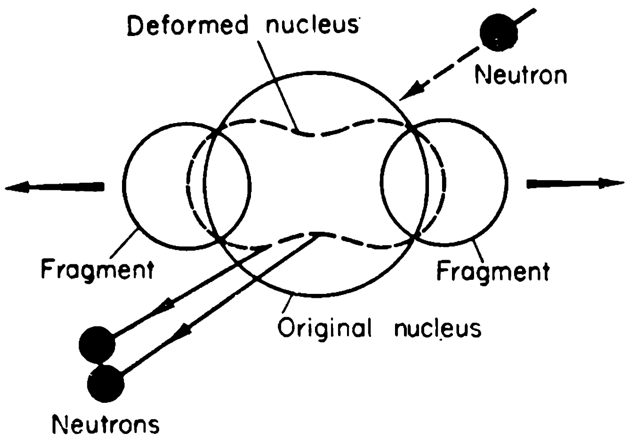


FIG. 19. Process of nuclear fission.

up in the atomic nucleus. "In the history of physics it often happens that a new discovery, which at first seems to have only a purely scientific interest, has, in the end, useful practical applications" (Rutherford). This also happened with the process of fission of the atomic nucleus.

It has become clear that under certain conditions the process of fission may acquire a chain or avalanche-like character; one fission will provoke a chain of subsequent fissions in the other uranium nuclei. The possibility of such a process is explained by the fact that on the fission of the nucleus, in addition to the fragments, two of three neutrons fiy out with high velocity. Each of them is capable, under favourable conditions, of causing the fission of another uranium nucleus, out of which, again, neutrons fly. The number of neutrons, and consequently also

of nuclei undergoing fission, increases with enormous speed, so that all the nuclei contained in a piece of uranium weighing about 1 kg undergo fission in a millionth part of second.

Such a process can take place in only one of the isotopes of uranium—uranium-235. The principal isotope—uranium-238 (constituting 99·3 per cent of natural uranium)—can be fissioned only by very fast neutrons, whereas comparatively slow neutrons are captured forming uranium-239. The latter is unstable, and after undergoing in succession two types of radioactive decay, is transformed into the nuclei of two new elements with $Z = 93$ (neptunium) and $Z = 94$ (plutonium).

The peaceful use of the energy evolved in the fission of uranium is realized in a controlled chain process. This process makes use of the fact that some of the neutrons are not formed instantaneously, but are produced by the fission fragments after a delay of several tenths of a second. These delayed neutrons make it possible to control the speed of the process. Usually in a nuclear reactor pure uranium-235, the production of which is extremely expensive, is not used, but natural uranium or a mixture enriched to several percentages with uranium-235. In this case the property of uranium-238, which weakly absorbs neutrons of low energy—thermal neutrons—is utilized. If we set up conditions under which the fission neutrons are effectively slowed down, then a chain reaction will proceed in spite of the presence of a large number of nuclei of uranium-238. As a moderator heavy water is used (water containing heavy hydrogen—deuterium) or graphite.

In nuclear reactors the uranium is not generally mixed with the moderator, but the latter fills the space between the uranium rods. In this way the uranium nuclei are removed from the region where the neutrons are being slowed down, and consequently the number of neutrons captured by uranium-238 is reduced.

In nuclear reactors colossal fluxes of thermal neutrons are obtained. There pass through every cm^2 of the active zone of a reactor up to 10^{14} neutrons per sec. Thus it is clear that

reactors form the principal source of radioactive isotopes, which are formed in quantities counted in tons.

Part of the radioactive products in a reactor consists of the fragments of the uranium nuclei. In addition, large numbers of radioactive substances are formed in special channels, where different elements are irradiated with neutrons.

CHAPTER III

PHYSICISTS NEED MORE PARTICLES OF HIGHER ENERGY

5. LINEAR RESONANCE ACCELERATORS

The attempt to construct high voltage accelerators has shown that the realization of currents of fast particles with energies greater than a few million eV is a very difficult problem. The dimensions of the accelerators increased, reaching several metres, but the voltage could hardly be increased at all.

For this reason, in the thirties, new methods of acceleration, which did not require the production of very high voltages, were more and more vigorously pursued. The idea of these methods was as follows: in order to obtain protons with energies of 10 MeV in a high voltage accelerator, they had to be accelerated in an electric field with a potential difference of ten million volts. But the protons could attain the same energy of 10 MeV by passing successively two hundred times through an electric field with a potential difference of fifty thousand volts. The production of such a field is technically comparatively simple. It was necessary, however, to solve another important problem: how to cause the particles to pass through a number of accelerating intervals. How was this to be done?

Let us try connecting the intermediate electrodes in the familiar ionic tube in the way shown in Fig. 20. Then we shall have two groups of electrodes—one connected with the positive pole of the source of voltage (*1, 3*) and the other with the negative (*2, 4*). Let us consider whether with this system there will be a multiple acceleration of the particles.

Positively charged particles emitted by the ion source will actually increase their velocity in the first gap, since here they are in an accelerating field. Inside the second electrode, the protons will move under their own inertia, since they are not subject to the action of a field. But as they approach the

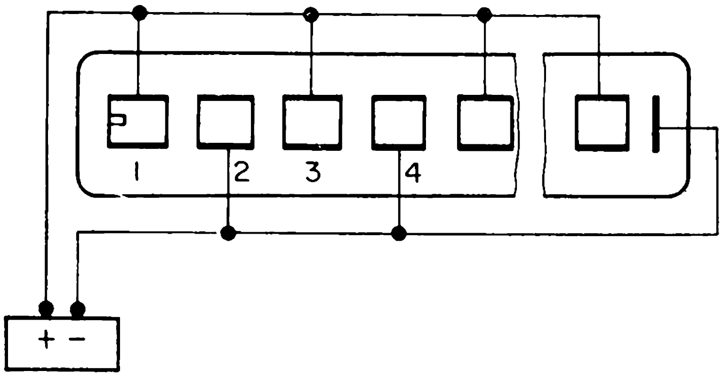


FIG. 20. Attempted multiple acceleration of particles with a small electric field.

second gap they will find themselves in a retarding electric field in which they will lose the energy previously acquired. Consequently, this simple form of the circuit of the accelerator will be unsuitable.

For successive multiple acceleration it is essential that in each gap the patricles should meet with a "following" accelerating field. Would it be possible, during the passage of the particles through the inside of the intermediate electrode, to reverse the terminals of the voltage source, thus changing the direction of the electric field in the gap from retarding to accelerating? Let us try to calculate the frequency with which it would be necessary to carry out such a commutation. The velocity of a proton with an energy of 50 keV, that is after passing through the first gap, amounts to 3500 km/sec. It will traverse a tube 10 cm long in a few ten-millionths of a second. Naturally no mechanical commutator can work within such a short period.

Scientists found a way out of this difficulty. They decided to use for the acceleration of the particles, not a generator of direct current with a commutator, but a high frequency generator of alternating current, similar to those used in radio stations. In these generators the direction of the current, and consequently the polarity of the voltage, changes millions or tens of millions of times per second.

Let us consider how an accelerator supplied from a high frequency generator (Fig. 21) would work. Let all the odd

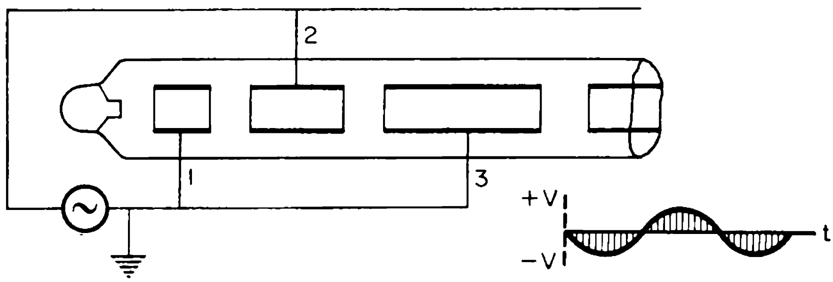


FIG. 21. Principle of the resonance accelerator.

intermediate electrodes be connected with the earthed terminal, and all the even electrodes with the high voltage terminal of the generator. Some of the protons emitted by the ion source will reach the first gap at the moment when the potential on the neighbouring electrode is $-V$, that is, the field will be an accelerating field. As these particles pass through electrode 2 the voltage on this electrode will increase, will become zero, and at the moment when the protons fly out of the electrode will become equal to $+V$. Since the following third electrode is earthed, the electric field will once more have the necessary direction and the protons will once more be accelerated. For successful acceleration it is necessary that the accelerated particles should always enter an accelerating field on approaching a gap. This means that the time which the particles take to pass between two neighbouring gaps must not change. But the speed of the particles continually increases. Consequently the

intermediate electrodes must have a variable and increasing length. In this case the time of passage through the electrode tube, equal to the ratio of the length of the tube to the speed of the particles, will remain the same and equal to a half-period of the high frequency generator.

This is called a resonance method of acceleration. Resonance is the name given to the phenomenon of the great increase in the amplitude of forced oscillations when the frequency of the external force approaches the frequency of free vibration of a body. The phenomenon of resonance has very varied applications in different branches of science and technology. As an example we can mention radio technology, where at every step the resonance properties of electric circuits are employed. In acceleration by a resonance method the frequency with which a particle enters the accelerating gap must be equal to the frequency (in our case to double the frequency) of the generator which produces the accelerating electric field.

The resonance accelerator just described was called a linear accelerator. The particles move approximately in straight-line paths. The increase in the energy of the particles in such an accelerator takes place discontinuously, by jumps. The magnitude of each jump depends not only on the value of the maximum voltage of the high frequency generator, but also on the moment, or as we say, the phase, in which a particle enters the accelerating gap. If passage through the gap takes place at a moment when the voltage is greatest, then the phase θ is said to be equal to zero. If the voltage has somewhat fallen, then the phase θ_1 is said to be positive (Fig. 22, right-hand portion), and conversely, if at the moment when the particle passes through the gap the voltage has not yet reached its maximum value the phase θ_2 is said to be negative.

If exact resonance is maintained the phase of the particles remains constant during acceleration, and a particle will acquire the same additional energy in every gap. The velocity of the particle will rapidly increase. It was precisely this fact which made the use of linear accelerators difficult. In the

thirties, generators of sufficiently short waves did not exist, and it was necessary to use extraordinarily long tubes. For this reason linear accelerators were used for the acceleration of heavy particles, which had lower velocities.

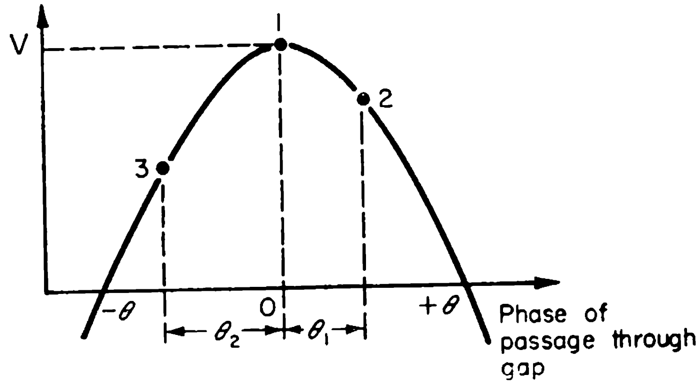


FIG. 22. Different phases of the transit of particles across the accelerating gap.

Another kind of resonance accelerator—the cyclotron—was more widely used.

6. THE CYCLOTRON

The inventor of the cyclotron—the American physicist Lawrence—was struck by a very clever idea: that of forcing the accelerated particles to move not in straight lines but in circles. The advantage of this method of acceleration is obvious: the need for long accelerating tubes was at once removed. But how could we force the particles to move in a circle? It turns out that for this purpose it is sufficient to place them between the poles of an electro-magnet excited by a direct current.

In a constant magnetic field a charged particle will move in a circle of constant radius, so long as its velocity and mass remain unchanged. In this case the particle is acted upon by two equal but oppositely directed forces: in the first place, the Lorentz force F_L, directed along the radius towards the

centre of the circle, as can be easily seen from the well-known left-hand rule (Fig. 23), and secondly the centrifugal force F_c. Since both these forces are directed perpendicularly to the velocity of motion, they do not perform work, and the motion, in the ideal case, will go on indefinitely. What will happen,

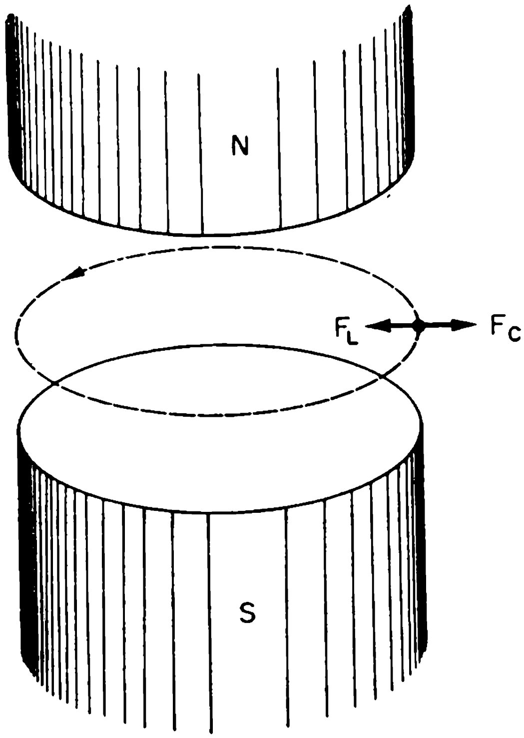


FIG. 23. Motion of a charged particle in a constant magnetic field.

however, if in some way energy is communicated to the particle? In this case the radius of its rotation will increase.

It is a fact of decisive importance that the frequency of rotation of a charged particle in a constant magnetic field does not depend upon its energy.

Actually,

$$\frac{mv^2}{R} = \frac{Hev}{c},$$

where the left-hand side of the equality is the centrifugal force and the right-hand side the Lorentz force.

Hence

$$\frac{v}{R} = \omega = \frac{He}{cm}.$$

It was this fact which made it possible to use a high frequency electric field for accelerating the ions in the cyclotron, as in linear accelerators.

Let us now consider the construction of the cyclotron (Fig. 24). In the pole gap of the electro-magnet, two metallic electrodes are placed. The voltage of a high frequency generator is applied to these electrodes, which are called Dees owing to the similarity of their form to the letter D. A source of positively-charged ions is placed near the centre of the magnet in the gap between the dees. The whole system of the electrodes and the ion source is placed in a vacuum chamber, from which the air has been evacuated to a pressure of 10^{-5} mm of mercury. An ion emitted by the source, at the time when the electrode *I* has a negative potential, is accelerated in the gap between the dees and enters the hollow inside the dee *I*. There it describes a semi-circle of constant radius, since inside the dee there is no electric field. If the frequency of the generator is properly chosen, at the moment when the ion emerges from the inside of *I* the voltage of the electric field changes and is reversed. Thus the ion is once more accelerated, and inside dee *II* describes a circle with a radius which is already greater.

Thus, moving in resonance with the high frequency field, the ions will rotate in a widening spiral towards the edge of the pole of the magnet. Their energy will increase after each passage through the accelerating gap between the dees.

The principle of the cyclotron can be explained by a simple example. A man standing on the ground swings a child in a swing. Every time the swing passes him, the man gives it a push, communicating to it an additional velocity. Although

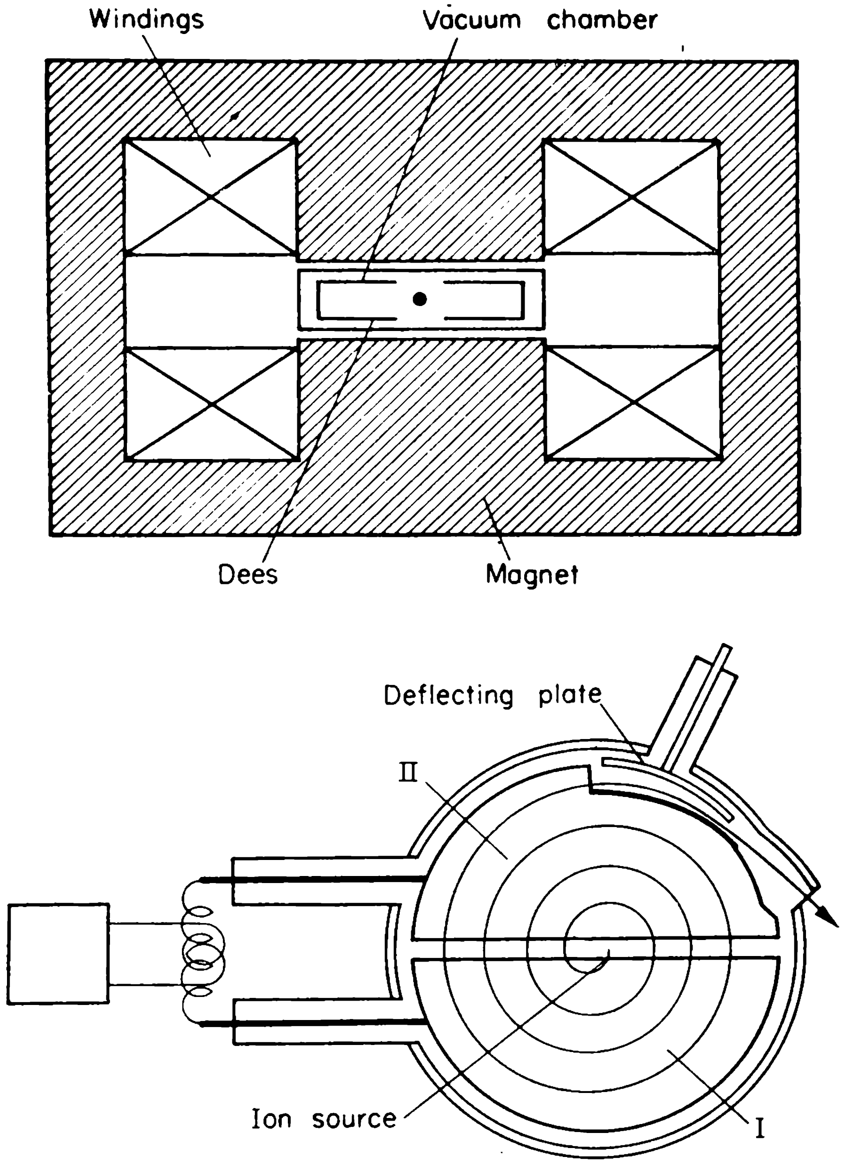


Fig. 24. Construction of the cyclotron.

the swing rises each time higher and higher, it passes its lower point after approximately the same interval of time. The action of the man in this example is analogous to the action of the high frequency generator of a cyclotron, which communicates energy in small increments to the stream of ions. The process

of acceleration will continue until the particles reach the edge of the poles of the magnet. A target is placed in the path of the current of particles, and when they fall upon it they produce a nuclear reaction. More often the beam of accelerated particles is directed out of the chamber by means of a deflecting electrode. This electrode, which is situated at the edge of the chamber, has a high negative potential. Under the action of the electric field the beam of accelerated ions changes its path, passes out of the chamber through a window covered with a thin foil, and falls on to a target.

Let us consider for a moment some special properties of the cyclotron. The magnetic field, first used in this accelerator, makes it possible to give the paths of the ions a cyclical character. This is the origin of the name cyclotron. But in addition to this principal task the magnetic field also fulfils the function of focusing the beam. In the cyclotron the particles follow a considerably longer path than in other accelerators. At the same time the space in which the particles move cannot be made very great. The fact is that an increase in the distance between the poles of the magnet leads to a considerable increase in its weight and also an increase in the power required to work it. Hence in the cyclotron the focusing of the particles has to be especially accurate, and here also the magnetic field comes to our aid. If it is made not strictly uniform but slightly diminishing along the radius (Fig. 25), then the lines of force of the magnetic field will be curved outwards, the field will be "barrel-shaped". By again using the left-hand rule it is not difficult to see that in such a magnetic field there will be a focusing of the particles by height. They will be compressed towards the central plane between the poles. In fact, if an accelerated particle is in some way deviated, for example, upwards from the central plane, a force will be immediately exerted upon it tending to return it towards the centre (Fig. 25), due to the horizontal component of the magnetic field (the particle is supposed to be moving perpendicularly to the diagram away from the reader). Unlike the

electrical focusing already described, which acts only in the accelerating gap, magnetic focusing takes place without interruption, and hence it is considerably more effective than electrical focusing.

It must be noted that the decrease in the magnetic field from the centre towards the boundaries must be very small

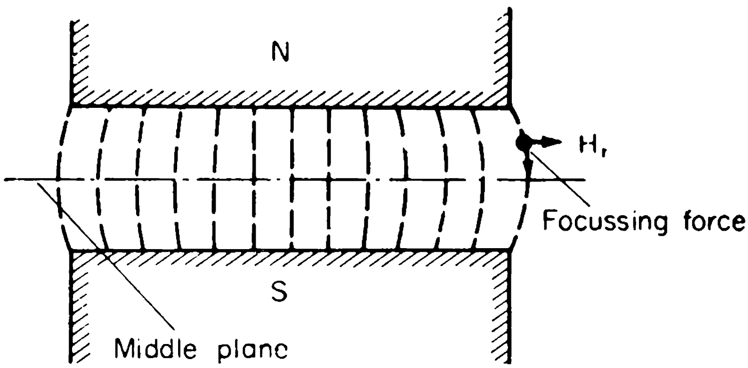


FIG. 25. Focusing of ions in the cyclotron.

(about 1 per cent), otherwise the principal condition of successful acceleration—the equality of the frequency of revolution of the ion and the frequency of the generator—will no longer be observed.

A very important part of an accelerator is the source of ions. Indeed its effectiveness determines a fundamental characteristic of the apparatus—the intensity of the beam of accelerated particles. The ion source of the cyclotron is a small metallic chamber into which hydrogen, deuterium or helium enters, depending on what ion is to be accelerated, under a pressure about a hundred times greater than the pressure in the chamber. An arc discharge takes place within the hollow vessel. The ions are extracted from the ionization column and accelerated by the high frequency field of the dees. Such a source can produce an ion current of several milliamperes.

As we have seen, the wavelength of the high frequency generator in the cyclotron is several metres, and is near to the

wavelength used in radio broadcasting. However, the function of the radio apparatus used in the cylotron is quite different; if in radio broadcasting we try to maximize the external radiation of power, in the cyclotron, on the other hand, we wish to make the loss by radiation as small as possible. The greater part of the power used in the cyclotron is applied to the creation of the high frequency accelerating field. In this connection we must consider the efficiency of the cyclotron. It

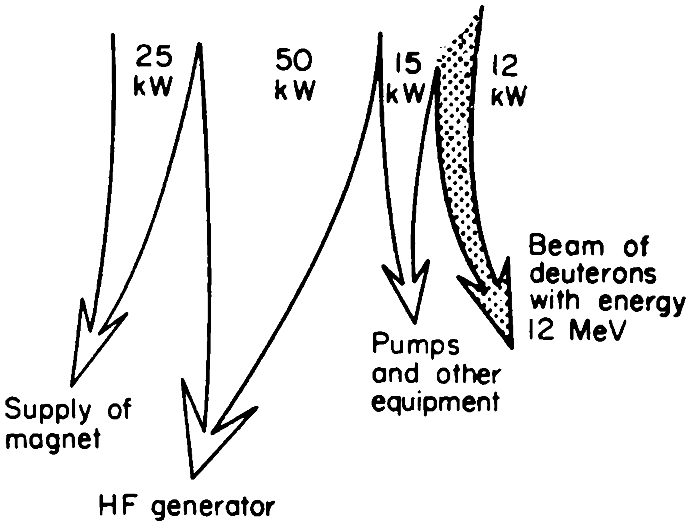


FIG. 26. Expenditure of power in the cyclotron.

may seem that its magnitude, that is the ratio of the power of the ion beam to the power absorbed by the cyclotron, is negligible. However, this is not the case. An estimate for a cyclotron in which the maximum energy of the deuterons is 12 MeV with a current of accelerated ions of 1 mA, gives a value of 13 per cent (Fig. 26). The power of the ion beam is very great—on 1 cm² cross-section of the beam there fall several tens of kilowatts. This energy is sufficient to melt any stationary target. Hence the targets in cyclotrons are often made to rotate, and in addition are vigorously cooled by water.

For a given value of the magnetic field, which particles will acquire the greatest energy in the cyclotron?

The value of the energy (for given value of H and R) depends on the ratio of the square of the charge of the ion to its mass.

If we take the mass of the proton as 1, then for the proton $Z^2/m = k = 1$, for the deuteron ($Z = 1$, $m = 2$) $k = 0{\cdot}5$ and for the α-particle ($Z = 2$, $m = 4$) $k = 1$.

Thus in a given cyclotron the greatest energy will be acquired by α-particles and protons, whilst deuterons will acquire only half of this energy. Moreover in the case of the acceleration of protons the wavelength of the generator could be diminished to half its former value. Actually

$$T = \frac{2\pi m \,.\, c}{HZe}.$$

Since m/Z for deuterons and α-particles is equal to 2, and for protons is equal to 1, the period of rotation for protons will be one-half that for deuterons and α-particles. If it is impossible to change the frequency, the protons will be accelerated only to one-half of the energy of the deuterons and the α-particles.

The cyclotron has proved a more successful accelerator than the earlier instruments. There are tens of cyclotrons at work in different countries of the world in which beams of protons, deuterons and α-particles of enormous intensity (up to 10^{16} particles per sec) have been obtained.

Streams of fast neutrons are also obtained by means of the cyclotron. Of course, neutrons cannot be accelerated in an electric field, since they have no electric charge. Beams of fast neutrons arise as the result of a nuclear reaction in the target of the cyclotron. For this purpose the target is made from elements for which there is a high probability of the nuclear reaction already described, leading to the expulsion of neutrons (e.g., beryllium).

There is also another method of obtaining fast neutrons, which was discovered somewhat later. This method depends on an entirely different type of nuclear reaction. If a beam of fast deuterons is directed on to the target, there is a high probability that the following remarkable process will take place.

Passing close to the nucleus, a deuteron (consisting of a proton and a neutron) "brushes against" the nucleus with its proton. The "stripped off" proton then remains in the nucleus, and the neutron belonging to the deuteron continues to move in the direction of the original beam with an energy of approximately half the energy of the deuterons.

In recent years ions with many charges, for example those of oxygen and hydrogen, have been accelerated in cyclotrons.

The most important application of the cyclotron is in the investigation of the properties of the nucleus; by its help many new nuclear reactions have been observed successfully on almost all the elements of the periodic system. These experiments have enabled physicists to achieve a considerable advance in their knowledge of the laws of the atomic nucleus.

We have already spoken of the artificial production of new chemical elements. The heaviest of these elements have been produced in cyclotrons. Thus, Fermium—the hundredth element of the periodic system—was first obtained by the bombardment of plutonium (the element with $Z = 94$, also artificially produced in atomic reactors) by nuclei of carbon accelerated in a cyclotron. And the hundred and first element, discovered immediately after fermium, and called Mendelevium in honour of the creator of the periodic system, was obtained in 1955 by a group of American physicists under the leadership of Seaborg, in a quantity of only seventeen atoms, by the bombardment of a target consisting of the element $Z = 99$ (Einsteinium) with α-particles from a cyclotron. The hundred and second element—Nobelium—the heaviest discovered up to the present time, was also discovered by means of the cyclotron. Reliable data about the new element were obtained in 1957–58 in the Soviet Union and United States.

An important application of the cyclotron is the production of radioactive isotopes. Until the construction of atomic reactors, only the cyclotron made possible the preparation of these isotopes in any considerable quantity.

This beautiful instrument of contemporary physics possesses, unfortunately, one important defect. It succeeds in accelerating ions only to comparatively low energies (protons not above 25 MeV). How does this limitation arise? We know that the fundamental principle of the cyclotron consists in "resonance" acceleration. It turns out, however, that the period of revolution of an ion in the cyclotron does not remain constant, but slowly increases in the process of acceleration. This increase is connected with the dependence of the period on the mass of the ion

$$T = \frac{2\pi mc}{Ze \, . H}.$$

In ordinary life the mass of a body is considered to be strictly constant. In fact, it depends on the velocity of the body. According to the theory of relativity put forward by Einstein and completely confirmed by experiment,

$$m = \frac{m_0}{1-\left(\frac{v}{c}\right)^2},$$

where m is the mass of the moving body, m_0 is the so-called rest mass, i.e. the mass of the body when stationary, v is the velocity of the body's motion, and c is the velocity of light in a vacuum, equal to 300,000 km/sec (or more exactly, 299,793 km/sec). This velocity is the highest obtainable in nature. In Fig. 27 the relationship between the mass and the velocity is shown graphically. The ratio of the velocity of the body to the velocity of light in a vacuum, $\beta = v/c$, is drawn along the horizontal axis, and the mass of the body as a ratio to its rest mass is drawn along the vertical axis. So long as the velocity of the body is small in comparison with the velocity of light its mass is hardly distinguishable

from its rest mass. For this reason, the increase of mass with velocity is not observed for the "coarse" objects with which we are surrounded. Thus, for example, the jet plane TU-104, which flies with a velocity of 1000 km/hr, increases in mass as it flies by only one-millionth part of a gramme. A different

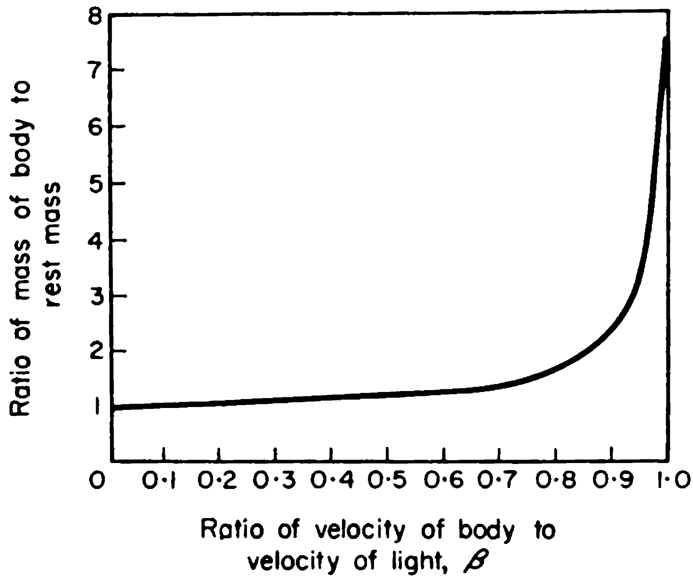


FIG. 27. Relation of mass of a body to its velocity.

picture is observed in the world of micro-particles, whose speed may differ only slightly from the velocity of light.

The ions after acceleration in the cyclotron have a mass noticeably greater than at the beginning of the acceleration. Hence the period of rotation increases with the acceleration, whilst the period of the high frequency field does not change. As a result, the ion arrives at the accelerating gap later and later each revolution, thus acquiring less energy (Fig. 28 points *2*, *3*), until it ends up in a retarding field (point *4*). Hence it would seem to follow that resonance acceleration is possible only so long as the mass of the ion does not differ very much from its rest mass. This was the unhappy conclusion to which the makers of cyclotrons came in the pre-war

years. The subsequent development of science, however, has refuted this conclusion.

Before describing the way in which this difficulty was overcome, we will pause to consider one non-resonance accelerator

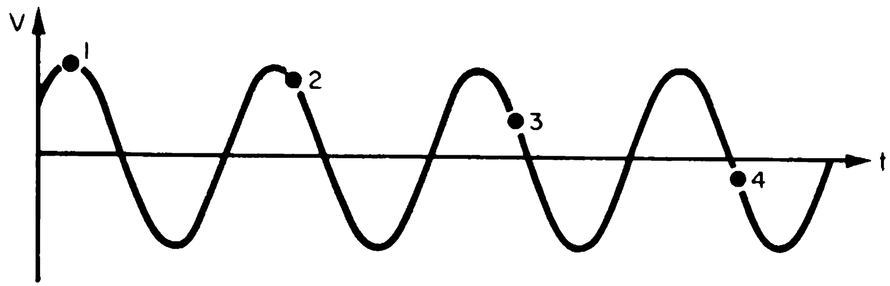


FIG. 28. Mass-change of particles interferes with working of cyclotron.
1, 2, 3 and *4*—successive phases of particles in the accelerating gap.

of electrons—the betatron—in which the velocity of the particles approximated closely to the velocity of light.

7. "ALMOST WITH THE VELOCITY OF LIGHT"

Is it possible to communicate to a body a velocity equal to that of light? From the relationships quoted in the previous chapter it would seem that in that case the body would possess an infinitely great mass. But it is rigorously proved in the theory of relativity that the mass m is connected with the energy E by the relationship $E = m.c^2$. Consequently it is only by communicating to a body an infinitely great energy that we can give it a velocity equal to the velocity of light. However in practice it is possible to obtain velocities very near to that velocity. The relationships between energy and velocity for protons and electrons are shown in Fig. 29, *a* and *b*. From these diagrams it will be seen that a proton with an energy of 20 MeV will move with a velocity $v = 0{\cdot}2c$ ($\beta = 0{\cdot}2$), whilst an electron with the same energy will have a much greater velocity ($\beta = v/c = 0{\cdot}99$). But how is it possible to communicate such an energy to an electron? If we

try to accelerate electrons in the cyclotron, the acceleration comes to an end owing to the increase of the mass at an energy considerably less than in the case of protons. It is easy to show that the energy of electrons accelerated in a cyclotron will be as many times less than the energy of protons

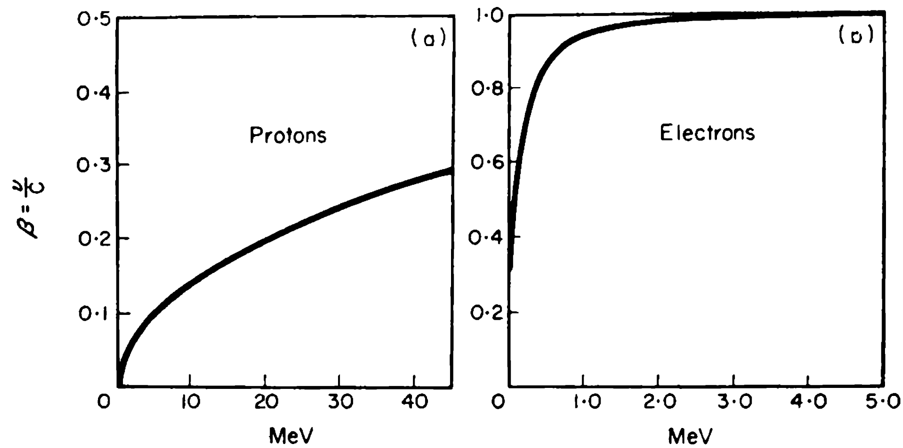


FIG. 29. Relation between energy and velocity for protons (*a*) and electrons (*b*).

as the electron is lighter than the proton, i.e. approximately two thousand times less, and will amount to only 10 keV.

Hence it is clear that the cyclotron is not suitable for the acceleration of electrons. Even before the appearance of high voltage accelerators, which made it possible to accelerate electrons up to energies of several MeV, in the twenties, the idea of the inductive acceleration of electrons appeared. In order to understand it let us recall the construction of a well-known piece of apparatus—the electrical transformer—based on the phenomenon of electro-magnetic induction. In the transformer, two windings are wound on the core. When an alternating current is passed through one of these windings, a pulsating magnetic field is produced in the core. It induces in the secondary winding of the transformer an electromotive force. If we close the secondary winding a current will flow through

it (Fig. 30, *a*). But what will happen if, instead of the secondary winding, the core of the transformer is surrounded by a vacuum chamber into which electrons are introduced (Fig. 30, *b*)? In this case also the rotational electric field produced by the alternating magnetic field will compel the

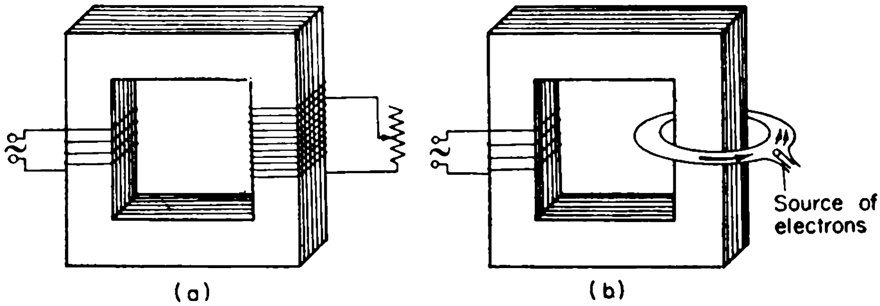


FIG. 30. Inductive acceleration of electrons.

electrons to rotate in the chamber. If nothing prevents the motion of the electrons they may acquire a considerable energy during the time when the magnetic field in the core of the transformer is increasing. This apparently simple idea of inductive acceleration met with serious difficulties when attempts were made to realize it, so that the construction of such an instrument seemed unrealistic to many people.

Only in 1940, when the necessary theoretical and experimental data had been accumulated, was a small inductive accelerator first set to work, accelerating electrons to an energy of 2·3 MeV, and called by its constructor, the American D. Kerst, the betatron (accelerator of electrons) (Fig. 31).

For the successful construction of an inductive accelerator it was necessary to solve two problems. In the first place it was necessary to find the conditions which would make it possible to keep an electron in an orbit of constant radius, and secondly, to ensure that motion in this "equilibrium" orbit should be stable. The first problem was solved by the Swiss physicist Videroy. In order that a particle should move in a magnetic

field H_0 in a circle of constant radius R, it was necessary that its momentum (the product of its mass and its velocity) should increase proportionally to the growth of the magnetic

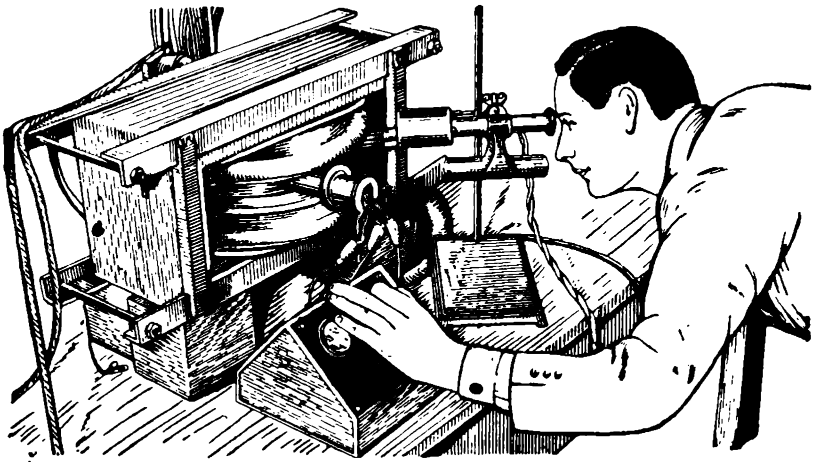


FIG. 31. Kerst's first betatron.

field in the orbit of the particle. This can be seen from the formula

$$R = \frac{cmv}{eH_0}.$$

But the momentum of an electron in the inductive accelerator increases owing to the change in the magnetic flux passing through the plane of the orbit of the electron (Fig. 32). Hence it was necessary to find a relationship between two magnetic fields: the field directing the motion of the electron (H_0—the intensity of the field in the orbit) and that accelerating the electron (H_y—the mean intensity of the field inside the orbit). Videroy's calculation led to the following simple relationship between the controlling and the accelerating magnetic fields. At any moment in the acceleration, the intensity of the magnetic field at the orbit of the electron must be half the mean intensity of the field within the orbit.

This can be made clear by the following example: take a single coil of wire whose radius is that of the equilibrium orbit of the electron. At a certain point in the orbit place a coil with a total area of its turns equal to the area of the large coil. Then from the "2:1" condition the voltage at the

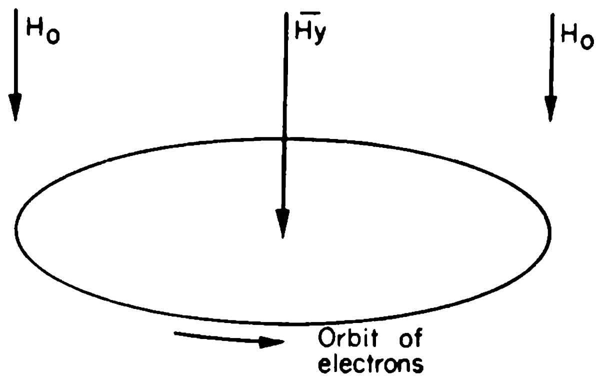


FIG. 32. Diagram of magnetic field in the betatron.

ends of the large coil, induced by the alternating magnetic field, must be twice as great as the voltage in the coil. It is curious that the motion of the electron in a circle of constant radius is conditioned in the betatron only by the ratio of two magnetic fields and is in no way connected either with the change of mass and velocity of the electron or with the law of increase of the magnetic fields. Thus, in contrast with the cyclotron, the betatron has no need to fear the increase in the mass of the accelerated electrons, however great it may become (electrons accelerated in the betatron to 20 MeV have a mass forty times greater that their rest mass).

The stability of the motion of the electrons in the betatron is of special significance. As distinct from the cyclotron, where the motion of the ions is little compressed in the horizontal plane, in the betatron the acceleration of the electrons takes place in a ring-shaped hollow vessel (Plate 2). Hence in addition to focusing in height there is an additional necessity for radial focusing.

In the cyclotron the magnetic field must reduce from the centre to the edges in order to obtain vertical focusing.

The non-uniformity of a magnetic field is usually characterized by the coefficient of reduction n.

In general

$$H_2 = H_1 \left(1 - n \frac{\Delta r}{r}\right)$$

where H_1 is the intensity of the magnetic field at point 1, H_2 is the intensity at point 2, situated on the radius through 1 at a distance Δr from the former in the direction of the edge of the pole.

In order to ensure focusing in the vertical plane, it is sufficient that n should be greater than zero ($n > 0$) i.e. that the field should weaken towards the edges. But what conditions must the magnetic field satisfy in order to ensure radial focusing? The Lorentz force and the centrifugal force which act on a particle in the equilibrium orbit differ in the character of their reduction with increasing radius from the centre of the orbit. The centrifugal force diminishes proportionally to $1/r$, and the Lorentz force to $1/r^n$. Hence the Lorentz force will diminish along the radius more slowly the smaller the value of n when n is less than 1 (Fig. 33 *a*).

For such a value of n a chance deviation of the electron from the equilibrium orbit will lead to one of these forces being greater than the other, so that in this case the resultant of the two forces will always return the electron to the equilibrium orbit.*

It is easy to see that when $n > 1$ (Fig. 33 *b*) there will be no stable motion, since a chance deviation of the electron from the equilibrium orbit will produce forces which will still further increase the initial deviation.

Thus in the betatron, when the reduction in the magnetic field along the radius takes place according to the law $0 < n < 1$,

* More exactly, the electron will describe damped oscillations round the equilibrium orbit.

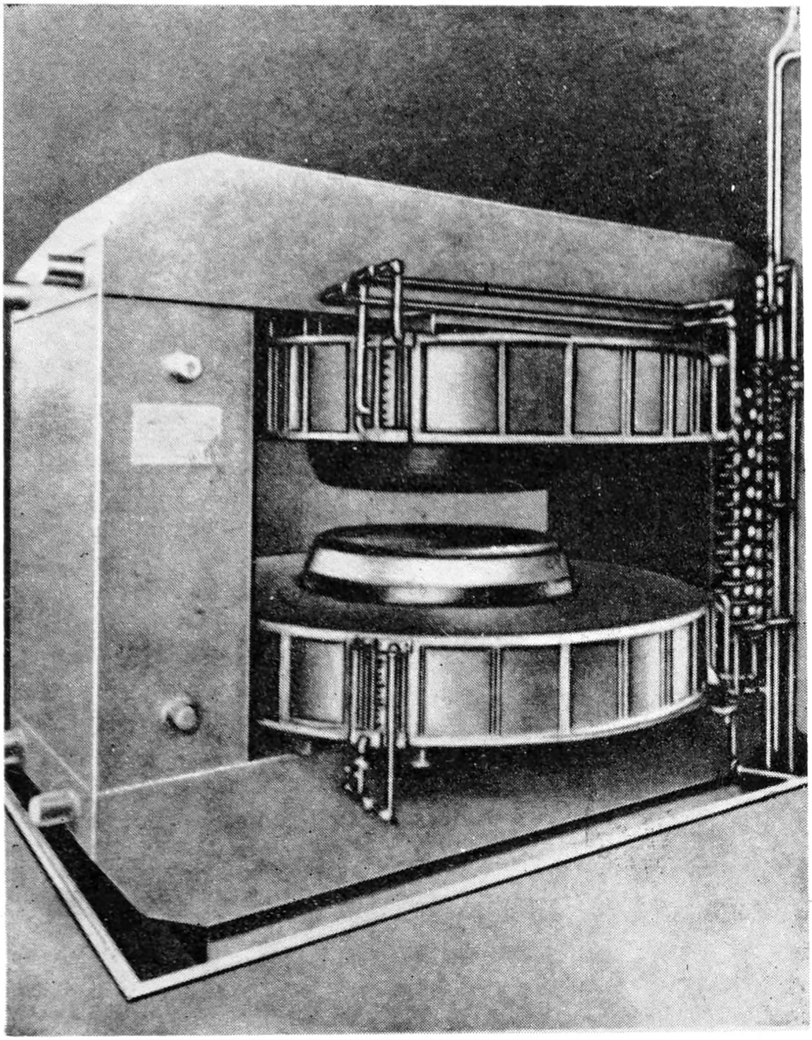


PLATE 1. Magnet of a cyclotron without the accelerating chamber.

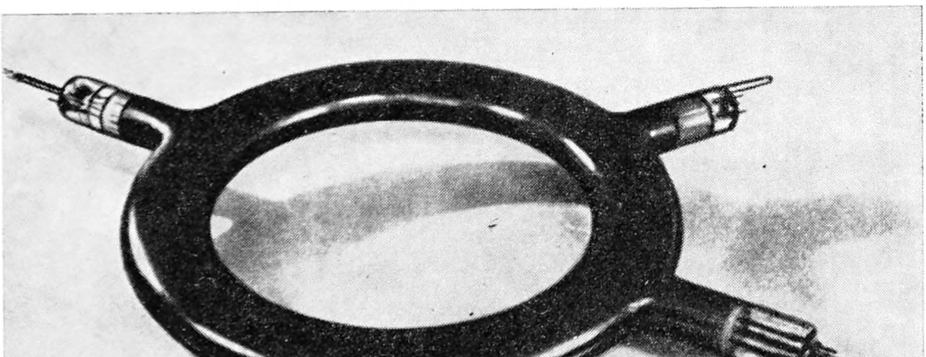


PLATE 2. Accelerating chamber of betatron.
For convenience in use the chamber is sealed.

there will be focusing both in the vertical plane and along the radius. In order to obtain the required value of n the poles are given the form shown in Fig. 34. Usually the coefficient n is taken equal to 0·6–0·7, corresponding to more powerful

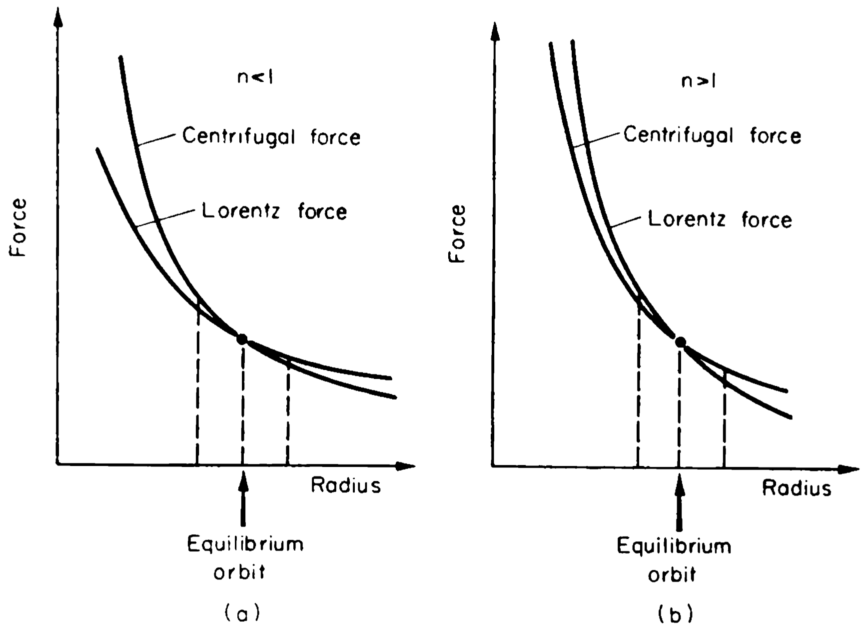


FIG. 33. Radial focusing in the betatron.

vertical focusing. This is done in order to reduce the gap between the poles, thereby reducing the weight of the magnet and the power expended in supplying it. The cross-section of the acceleration chamber of the betatron has the form of an ellipse whose horizontal axis is longer than its vertical axis.

Let us now consider the construction of the betatron. Figure 34 represents a diagrammatic view of the accelerator. The most important part of the betatron is the electro-magnet. Like a transformer, it is built up of individual mutually insulated sheets of steel, in order to prevent the appearance of eddy currents under the action of the alternating magnetic field. Otherwise the eddy currents very much distort the distribution of the magnetic field in the pole gap. The magnet pos-

sesses side yokes and poles, in the gap between which the accelerating chamber is situated. An alternating current from the supply mains is delivered to the windings on the poles.*

In order to reduce the active power absorbed by the magnet, a secondary high voltage winding on the poles was connected

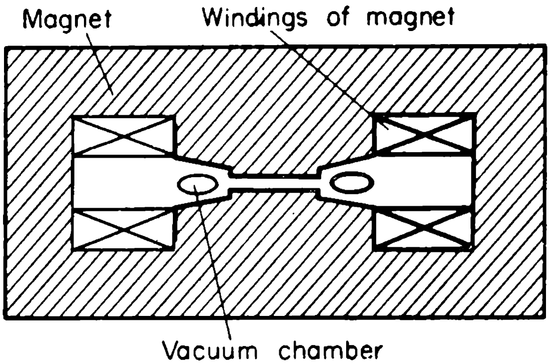


FIG. 34. Diagrammatic cross-section of betatron.

with a battery of condensers. The capacity of these was so chosen that the magnets and the battery formed a resonance circuit tuned to the frequency of the electric mains. The accelerating chamber of the betatron, which is made of glass or porcelain, has the form of a ring. Since the electrons move in a circle of constant radius, there is no need here for a chamber which is continuous across its diameter. At the same time the absence of a large air gap in the centre of the magnet makes it easier to pass the accelerating magnetic flux through the orbit.

The chamber is provided with radial side tubes. One of these communicates with the vacuum pumps which produce a vacuum of about 10^{-6} mm in the chamber. Another side tube serves for the introduction of electrons into the chamber. This

* The frequency of the alternating currents used to feed the windings of the magnets of the first betatrons was higher than usual, a fact which to some extent increased the intensity.

is performed by means of a special apparatus called an electron gun or injector. This apparatus consists of a tungsten filament, which projects a beam of electrons, and a system of electrodes which focus the beam and communicate to it an energy of several tens of keV. Electrons are injected into the chamber in the course of several micro-seconds (millionth parts of a second), just after the increasing magnetic field on the orbit exceeds the zero value. Only a small fraction (a few per cent) of the total number of electrons injected into the chamber takes part in the process of acceleration. The greater number of the electrons settle on the walls of the chamber. In order to avoid the accumulation of electric charges on the inner wall of the chamber, a very thin conducting film (e.g. of silver) is deposited on the inner wall, which is thus earthed. So long as the magnetic field increases, the energy of the electrons will increase. The energy acquired in each revolution amounts to several tens of electron volts, but owing to their colossal velocity the electrons complete up to a million revolutions during the time that the magnetic field is growing (this is equal to a quarter of the period or 1/200 sec). Thus, the enormous energy of some tens of MeV is communicated to the electron. In certain cases the beam of accelerated electrons is led out of the chamber of the betatron. As a rule, however, the beam is moved outwards from the equilibrium orbit by means of a current pulse in special windings of the magnet and, moving in a spiral, falls on a target which is usually the back-end of the electron gun.

Certain models of the betatron include an important improvement by which the power absorbed by the accelerator is considerably reduced. In addition to the ordinary alternating H_{alt}, an additional constant magnetic flux H_{const} is passed through the magnet (Fig. 35). In this way the zero of the magnetic field, which corresponds to the beginning of the acceleration, is moved from the point A to the point A' and the duration of the acceleration increases from a quarter of a period of the magnetic field to almost half a period. In

these betatrons with superimposed magnetization the iron losses due to the alternating magnetic field are considerably less.

Owing to the sharp retardation of the electrons on the target intensive γ-radiation is produced, similar to the radiation in

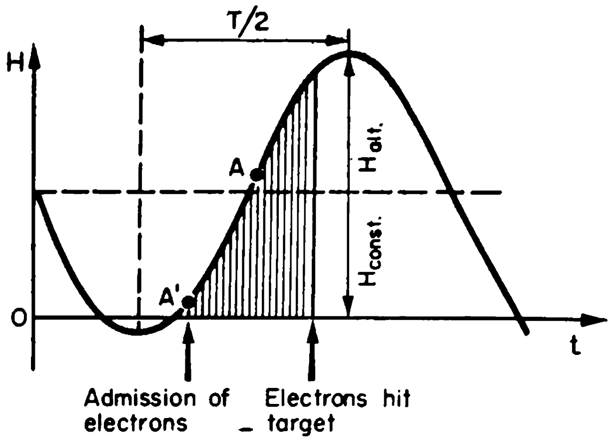


FIG. 35. Working of betatron with superimposed magnetic field.

Röntgen tubes. The beam of γ-rays is distributed within a narrow cone in the same direction in which the electrons were moving. The width of the beam depends on the energy of the accelerated electrons, and when $E = 20$ MeV amounts to several degrees.

The radiation from the betatron occurs in separate periods—pulses. After each period of change of the magnetic field a single pulse appears which lasts for fractions of a microsecond. We have already met with γ-quanta in investigating the phenomenon of radioactive decay. The γ-quanta formed in betatrons are of the same nature, but their energy may be considerably higher. The intensity of the γ-beam in the betatron is also incomparably higher. There is one more characteristic feature of the beam of γ-rays from the betatron. The beam contains quanta of all energies from the smallest up to the maximum possible energy, equal to the kinetic energy of the accelerated electron. This energy E_m is very easy to deter-

mine if we know the intensity of the magnetic field on the orbit H_0 and the radius of the orbit of the electrons R:

$$E_m \approx 300H.R - m_0c^2,$$

where H is in oersteds, R in centimetres, and E_m in electron volts.

Betatrons are very perfect and at the same time very convenient physical instruments. However, they require exact tuning. The symmetry of the magnetic field of the accelerator has also to be very exact. The working of the apparatus can be completely ruined even by the introduction of a small permanent magnet into the acceleration chamber. The reason for this "sensitiveness" is not difficult to understand. Asymmetry of the magnetic field in any place produces a corresponding distortion of the orbit of the electrons which, instead of being circular, becomes elongated. Great asymmetry will lead to acceleration being terminated, since the orbit will touch the internal or external wall of the chamber.

The greatest danger arises when the vector of the intensity of the magnetic field does not pass through the zero value at different points of the orbit at the same time. Suppose that at two points of the orbit A and B the graphs of the increase of the magnetic field are displaced relatively to one another by a small interval of time. Then at the moment when the magnetic field at the point B is equal to zero, at the point A it has already reached the value H_1. If at that moment (or shortly afterwards) electrons are injected into the chamber, their orbit will not be circular, and no acceleration will occur. Dangerous asymmetry of the magnetic field can be revealed by different methods, for example, by observing on the screen of a cathode oscillograph the pulses in special coils situated between the poles of the magnet. Their cores are made of the alloy "permalloy", which becomes saturated even in very weak magnetic fields. Thus at the moment when the magnetic field passes through zero in one of the coils there occurs a very

short pulse. If the passage through zero does not take place simultaneously at different points, the pulses are seen to be displaced in time. To correct the magnetic field in an accelerator, special correcting coils are used.

At the present time hundreds of betatrons are under construction in different countries. In the largest of them the electrons are accelerated to an energy of 300 MeV. Their velocity differs by only 0·03 per cent from the velocity of light, and their mass exceeds by 600 times the rest mass of the electron.

It might seem that it would not be difficult to construct accelerators which would produce particles of still greater energies. But this is not the case, In addition to the fact that the increase of energy carries in its train an enormous increase in the power absorbed (the weight of the betatron magnet for 300 MeV amounts to 1000 tons), there is also a difficulty of purely physical order which was first pointed out by the Soviet physicists D. D. Ivanenko and I. Ya. Pomeranchuk. An electron moving in a circular orbit in the betatron must lose considerable energy in the form of radiation. With increasing energy of the accelerated electrons the radiation grows rapidly and at an energy of several hundred MeV the radiation losses begin to exceed the energy acquired in the rotating field. Thus the induction accelerator has a definite energy "ceiling".

Betatrons are widely used in nuclear research. Hitherto we have considered the transformation of the nucleus under the action of protons, neutrons, α-particles, and deuterons. It turns out that γ-quanta also are able to disrupt the atomic nucleus. It is only necessary that the energy of the γ-quantum should exceed the energy with which a particle is held in the nucleus—the binding energy of the particle.

Betatrons are used not only for the study of the properties of the nucleus. They have applications also in technology and medicine, and also in the food industry for the sterilization of tinned products.

Let us consider briefly two applications of the betatron.

A beam of γ-rays with a maximum energy of 15–25 MeV possesses very powerful ionizing activity and at the same time great penetrating power. These properties render it possible to apply betatrons successfully to the discovery of defects in great thicknesses of metal. By placing a sensitive photographic film on the other side of a metal sample with a thickness of 5 cm, it is possible to detect the presence in the metal of cracks of a thickness less than 0·1 mm.

Interesting attempts have also been made to cure cancerous growths by means of γ-radiation from betatrons. The beam from the betatron is cut down to the required dimensions by means of lead collimators. Aluminium filters of a thickness up to 2 cm remove low energy γ-quanta from the beam. A great advantage of the medical application of betatrons in comparison with Röntgen apparatus is the possibility of obtaining a maximum dose of radiation at a depth of 6–7 cm. This makes it possible to use betatrons for the treatments of deep lying growths with less danger of injury to healthy tissues on the surface of the body.

In order to simplify the practical use of betatrons, especially those used for industrial and other applications, they are made with sealed accelerating chambers (Plate 2). The high vacuum in the chamber (10^{-6} mm) is maintained by means of a special apparatus called a getter, which, on heating, powerfully absorbs the residual gases. The service life of such a chamber amounts to 1000 hr.

CHAPTER IV

NEW IDEAS—NEW ACCELERATORS

8. PRINCIPLE OF AUTO-PHASING

The particle energies obtained in the cyclotron could not satisfy the scientists who were seeking to unravel the mysteries of nuclear structure. It was already known from Rutherford's experiments that the forces which bound the particles in the nucleus acted over very small distances of the order of 10^{-13} cm. These data also enabled the Japanese physicist Yukava, on theoretical grounds, to put forward the bold idea that rapidly decaying particles which were hitherto unknown must exist in nature.

Just as photons, appearing as the result of electro-magnetic interaction, were characteristic of electrical forces, the supposed particles must appear as the result of nuclear interactions and be characteristic of nuclear forces. According to the predictions of Yukava's theory, the new particles must have a mass intermediate between that of the electron and the proton. A few years later, scientists who were studying cosmic rays actually observed on photographic plates the traces of particles with a mass two hundred times greater than that of the electron. Later on still heavier particles, the π-mesons, were discovered which unlike the former (or μ-mesons) interacted with atomic nuclei. It is these π-mesons which are at present regarded as corresponding to the nuclear forces. Only by studying the properties of these mesons is it possible to understand the nature of these forces. But how were we to study the mesons in detail? It was difficult to do this by means of the cosmic rays, principally owing to their extremely low intensity. It

would be possible to study the behaviour of the new particles much more exactly if they were produced artificially in nuclear reactions. But in order that a meson might be formed high energy was required. The rest mass of a charged π-meson is equal to 273 electron masses, and an electron at rest corresponds to an energy of 0·511 MeV. Hence the energy of the π-meson at rest is equal to 141 MeV. Actually a substantially greater energy is required, since a considerable part of the energy is absorbed by the other particles formed in the process of the reaction. Thus, for example, in order that a π-meson might be formed in the course of the reaction $p + p = n + p + \pi^+$ the original proton must possess an energy not less than 293 MeV. That is why physicists awaited with such impatience the construction of accelerators with a particle energy of several hundred MeV. The problem of considerably increasing the energy of accelerators of charged particles was solved in 1944 by the Soviet physicist V. I. Veksler. Whilst studying the resonance acceleration of particles moving with high velocity, he discovered the interesting physical phenomenon which he called auto-phasing. All present-day accelerators are based on this phenomenon. What then is the auto-phasing of particles? Remember how, with the increasing mass of the ions, the acceleration in the cyclotron comes to an end (Fig. 36). When the high frequency period T_0 (solid line) remains constant, the period of revolution T of the ion increases,

$$T = \frac{2\pi mc}{eH},$$

and the particle arrives in the accelerating gap when the voltage in the gap has already somewhat decreased from the previous transit.

Now suppose that the high frequency period T_0 could somehow be smoothly increased during the process of acceleration. Then among the multitide of accelerated ions there will be some for which the increase in the period of revolution will be the same as the increase in the period of the high frequency

field. Consequently resonance would not be destroyed, and the "fortunate" particles would continue to be successfully accelerated at a constant phase of the field. But the "fortunate" particles are a very small part of the total number, and there

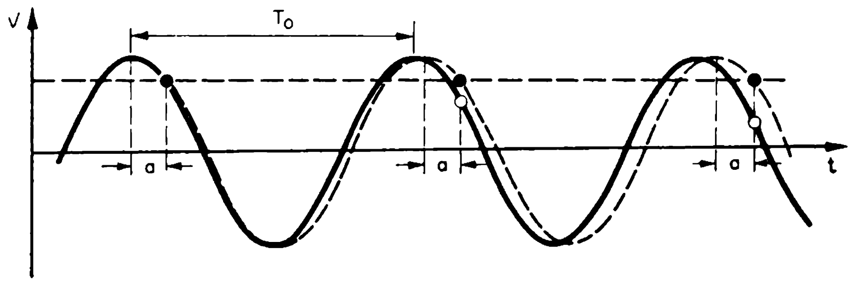


FIG. 36. Change of frequency in the cyclotron.

would be no question of constructing such an accelerator but for one remarkable circumstance. It turns out that not only the "fortunate" or equilibrium particles will continue to absorb energy in a cyclotron with changing period of high frequency. The remaining particles, which have approximately the same energy as the equilibrium particles, will also be accelerated, but in a somewhat different way. Let us consider the behaviour of a particle which initially acquires an energy less than that of the equilibrium particles. The smaller increase of energy corresponds naturally to a smaller increase in the mass and the period of revolution than in the case of the equilibrium particles. Consequently the particle will arrive at the gap somewhat earlier on the next occasion, and this means also at a somewhat larger voltage in the gap than the first time.

Thus gradually, revolution after revolution, the particle increases in growth of energy, until after several tens or even hundreds of revolutions (Fig. 37) the phase of the particle becomes equal to the equilibrium phase. But the particle does not remain in its phase motion, but begins to acquire an energy greater than the equilibrium energy. After a certain time the reverse process of the diminution of the growth of energy

begins. Thus the particle, so to speak, oscillates around the necessary phase φ_0, while—and this is very important—the amplitude of the phase oscillations decreases with increasing energy. If the increase in the period of the high frequency field takes place slowly, the value of the phase φ_0 around which the phase oscillations of individual particles take place will also change.

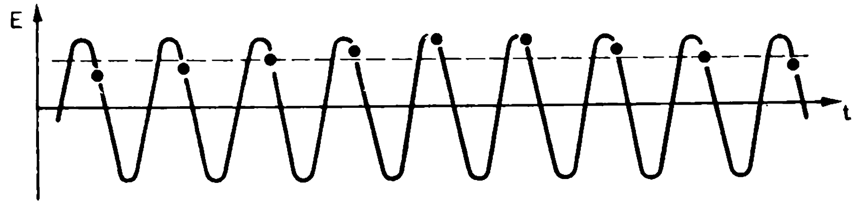


FIG. 37. Auto-phasing of particles in accelerator.

It is as though, in the process of acceleration, the particles automatically chose the phase necessary for their resonance acceleration. That is why this phenomenon has been called the auto-phasing of particles.

Thanks to auto-phasing, nearly all the particles which have begun to be accelerated are able to reach successfully the limiting energy determined by the radius of the magnet. But they will acquire energy in different ways (Fig. 38). The equilibrium particles will acquire energy in identical increments. The remaining particles will be accelerated non-uniformly—now faster and now more slowly. On the average the increase in energy will be the same for all the particles. It is not necessary to choose any rigorous law of change of the period T_0 of the accelerating field. It is important only that, towards the end of the acceleration, the period should increase by as much as the mass of the ions. It is also necessary that the potential difference on the dees should be large enough.

Veksler also pointed out a second possible use of the phenomenon of auto-phasing. It consists in the application of an increasing magnetic field with constant frequency of the accele-

rating electric field. The period of rotation of the ions in this case will remain constant.

Particles with an excess of energy will move with a greater radius than the equilibrium particles, and hence with each revolution will arrive at the accelerating gap later and later.

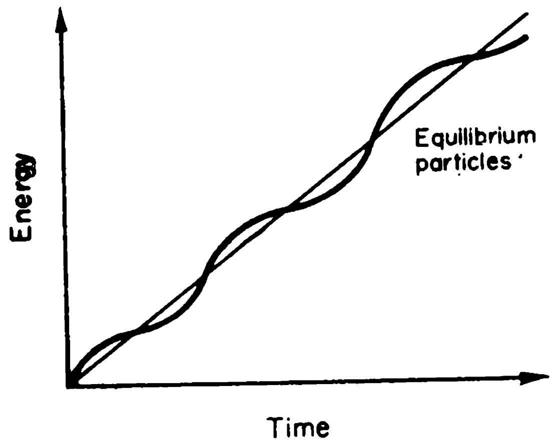


FIG. 38. Increase of energy of particles in process of auto-phasing.

The mechanism of auto-phasing will also operate in this case, but the particles will accommodate themselves to the change in the magnetic field.

In both the examples considered, thanks to auto-phasing, the accelerated ions will rotate on the average with the frequency of the external electric field.

Finally one more method of acceleration was proposed in which both the magnetic field and the frequency of the electric field were maintained constant. In this case the increase in the period of revolution of the particles must be an integral multiple of the period of the high frequency field. The discovery of the phenomenon of auto-phasing (this was also discovered by the American physicist Macmillan some what later) has played an enormous part in the development of accelerators. The barrier barring the increase in energy of the accelerated particles has been destroyed. In principle, auto-phasing makes

it possible to accelerate particles to any energy. The limit is now determined only by technical considerations.

Shortly after the discovery of auto-phasing, physicists constructed a number of different accelerators based on this phenomenon.

9. PHASOTRON AND SYNCHROTRON

In the phasotron the method of changing frequency of the electric field is employed. The phasotron, or as it is sometimes called the synchro-cyclotron, retains nearly all the features of its predecessor, the cyclotron. It has an electro-magnet, but

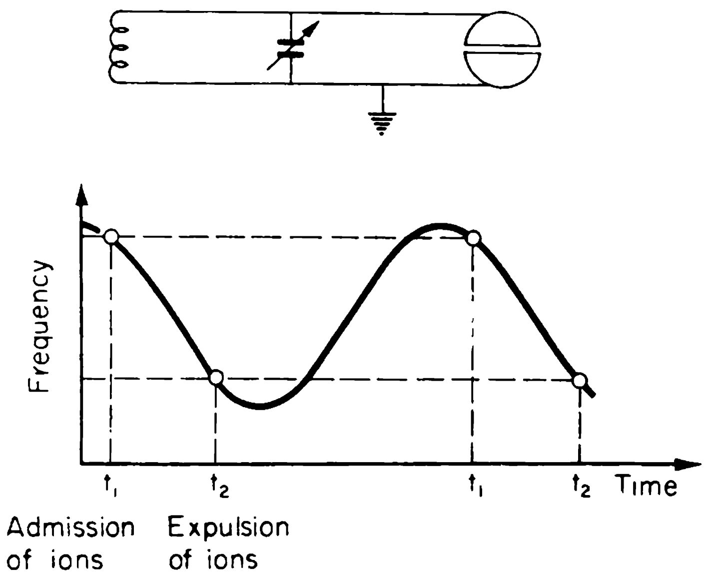


FIG. 39. Change of frequency in the phasotron.

of larger dimensions, a high frequency generator and a vacuum chamber. As in the cyclotron, the acceleration begins from the centre of the magnet. At the moment when the ions are introduced into the chamber the frequency of the electric field on the dees is near to the maximum (point t_1, Fig. 39). It corresponds to a zero velocity of the ions and consequently to a constant mass. As the velocity of the ions increases, the fre-

quency diminishes to its minimum value, which corresponds to the greatest energy of the ions. Somewhat earlier than this moment the accelerated particles either strike the target or are led out of the chamber (point t_2). After the frequency has again reached its maximum value a new cycle of acceleration begins.

Let us familiarize ourselves with the data of the largest phasotron, which has been at work in the Soviet Union since 1949 and belongs to the United Institute of Nuclear Research (Plate 3). In this accelerator protons reach an energy of 680 MeV. The magnet of the accelerator has the height of a three-storey house and weighs 7000 tons. The diameter of its poles amounts to 6 m. A considerable decrease in the magnetic field from the centre to the edges (4·9 per cent) ensures better vertical focusing of the beam than in the cyclotron. Here a greater decrease in the magnetic field can be permitted than in the cyclotron, without fearing that the particles will get out of resonance. The poles of the magnet are at the same time the covers of the huge vacuum chamber whose volume is more than 30 m^3. In the centre of the chamber, which is evacuated by powerful pumps, the ion source is situated. Hydrogen gas (in the case of the acceleration of protons) is fed to it from an external reservoir through tubes. Usually there is only one dee in the phasotron, the other earthed electrode being the vacuum chamber itself. A small alternating voltage (in comparison with that of the cyclotron) is applied to the dee of the phasotron. The amplitude of this voltage does not exceed 15–20 kV. During the acceleration of the protons to 680 MeV their mass increases by more than 72 per cent. In order to vary the frequency of the electric field during the acceleration of the ions, the following method is used. A condenser is connected to the dee of the phasotron, and one of its plates rotates in a vacuum at high speed. In consequence the capacity of the condenser, and consequently the capacity of the whole contour of the dee, changes periodically within the necessary limits. Correspondingly also, the frequency of free oscillation

of the contour of the dee also changes, since it depends on the capacity and inductance of the circuit. A high frequency self-excited generator connected with this contour produces in it oscillations with a frequency equal to that of the free oscillation of the circuit.

The intensity obtained in the phasotron is hundreds of times less than that obtained in the cyclotron. Such a considerable decrease in intensity is peculiar to all accelerators which make use of the phenomenon of auto-phasing, and is connected with the reduction in the time during which the particle is held in the accelerating field. If in the cyclotron the time during which the ions are held in the field covers a considerable part of the period, say one-seventh to one-ninth, in the phasotron only a negligible fraction of all the ions which are continually emitted by the source can be successfully accelerated. These will be the ions which have arrived in the chamber during that short interval of time when the frequency of the electric field corresponds to a zero velocity of the particles. Ions arriving in the chamber earlier or later will not be accelerated by resonance, since the frequency will no longer be suitable for them. But in this case there is no question of the continuous introduction of ions into the chamber. The ion source of a phasotron usually expels ions only during the time of capture by the field. Thanks to this fact it is possible to increase the impulsive ion current. On an internal target not far from the edge of the pole there fall $1{\cdot}8 \times 10^{12}$ protons per sec. The pulses follow one another at an interval of about $^1/_{100}$ sec.

It is considerably more difficult to lead the beam of protons out of the chamber. The pitch of the spiral along which the particles travel outwards in the phasotron is very small. Hence in this case we cannot effectively make use of a constant electric field to deflect the stream of particles as in the cyclotron. An original method of leading the beam out of the phasotron has been devised by specialists. At the proper moment at definite points inhomogeneities of the magnetic field are artificially produced. The orbits of the ions thus change their form and

the proton beam comes out of the chamber through a hole in a special magnetic screen. In this way up to 8 per cent of all the protons have been successfully led out of the chamber. Let us consider the arrangement of the apparatus near the accelerator (Fig. 40). Our attention is caught by the concrete wall many metres thick which surrounds the phasotron on all sides. This is necessary to protect people from the effect of the radiation. The proton beam itself can be easily absorbed, but when it falls on matter it gives rise to a large quantity of neutrons and γ-rays. These constitute the principal danger. We know that particles of enormous energy fall upon the earth from inter-stellar space, their quantity being by no means small. On each square centimetre of the surface of the earth on the average 1·5 particles fall per minute. This means that the body of every human being is penetrated every minute by thousands of energetic particles. However, this bombardment does not cause noticeable harm to people's health. The case is different with accelerators. The milliards of particles which are formed every second demand extensive protective measures. People working on accelerators or with radioactive materials carry with them instruments which make it possible to decide what dose of radiation they have received. And it is not only persons that require protection. All the research apparatus, with the exception of the targets, must also be protected from the effect of the radiation. Thus the beams of particles pass through the concrete protection of the phasotron by narrow channels. From the internal target of the phasotron we can obtain beams of neutrons, π-mesons and protons which are transmitted outside. The neutron beam, which is not subject to the action of the magnetic field, passes through the corresponding channel without deviation. The π-mesons are deflected by the stray magnetic field of the phasotron in opposite directions. An interesting novelty is the use of the iron yoke of the phasotron as a shield, beyond which the "meson laboratory" is situated. For the introduction of the mesons into the laboratory a hole is bored through the 3 m thick yoke of the magnet. Through this pass

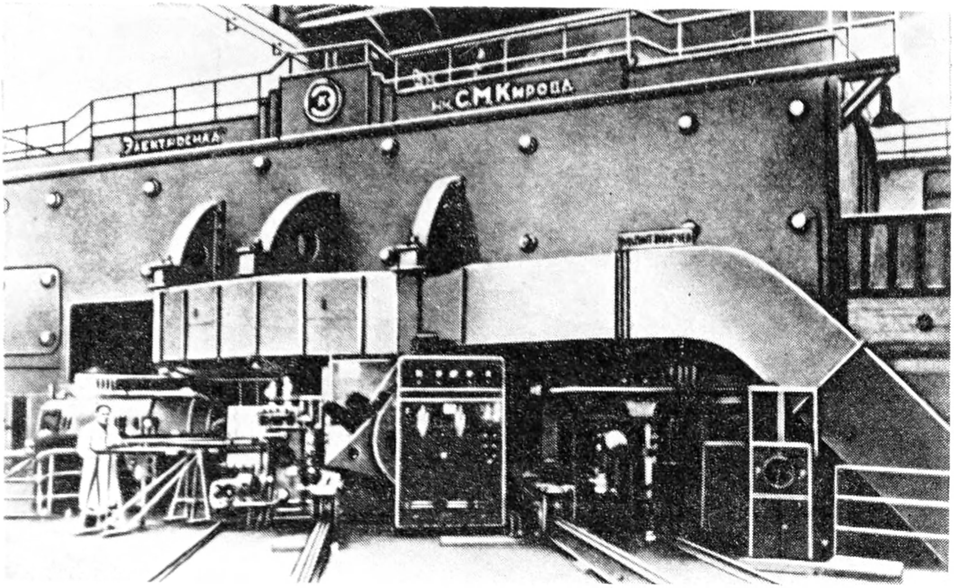


Plate 3. Phasotron of the United Institute of Nuclear Research at Dubno.

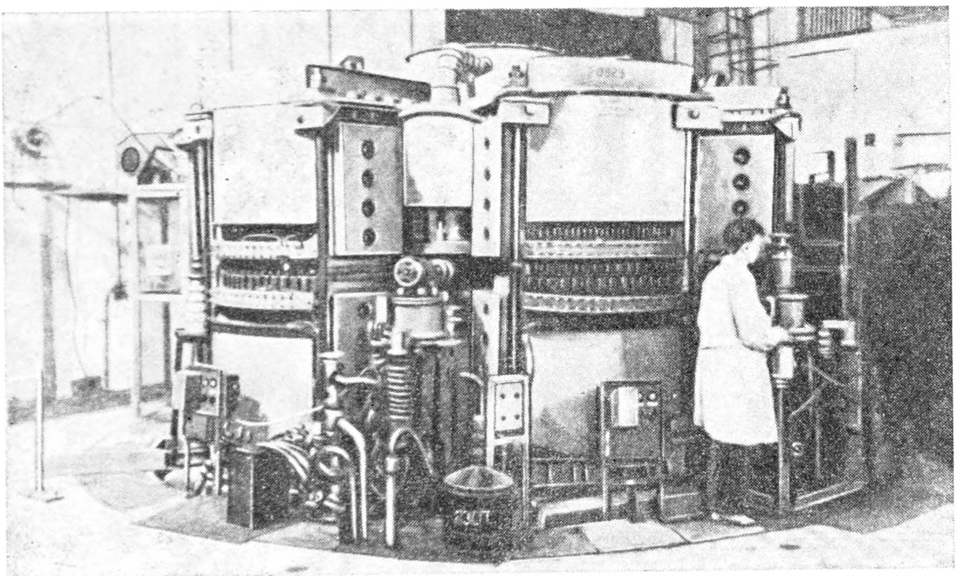


Plate 4. Synchrotron at the Lebedev Institute in which electrons are accelerated to an energy of 265 MeV.

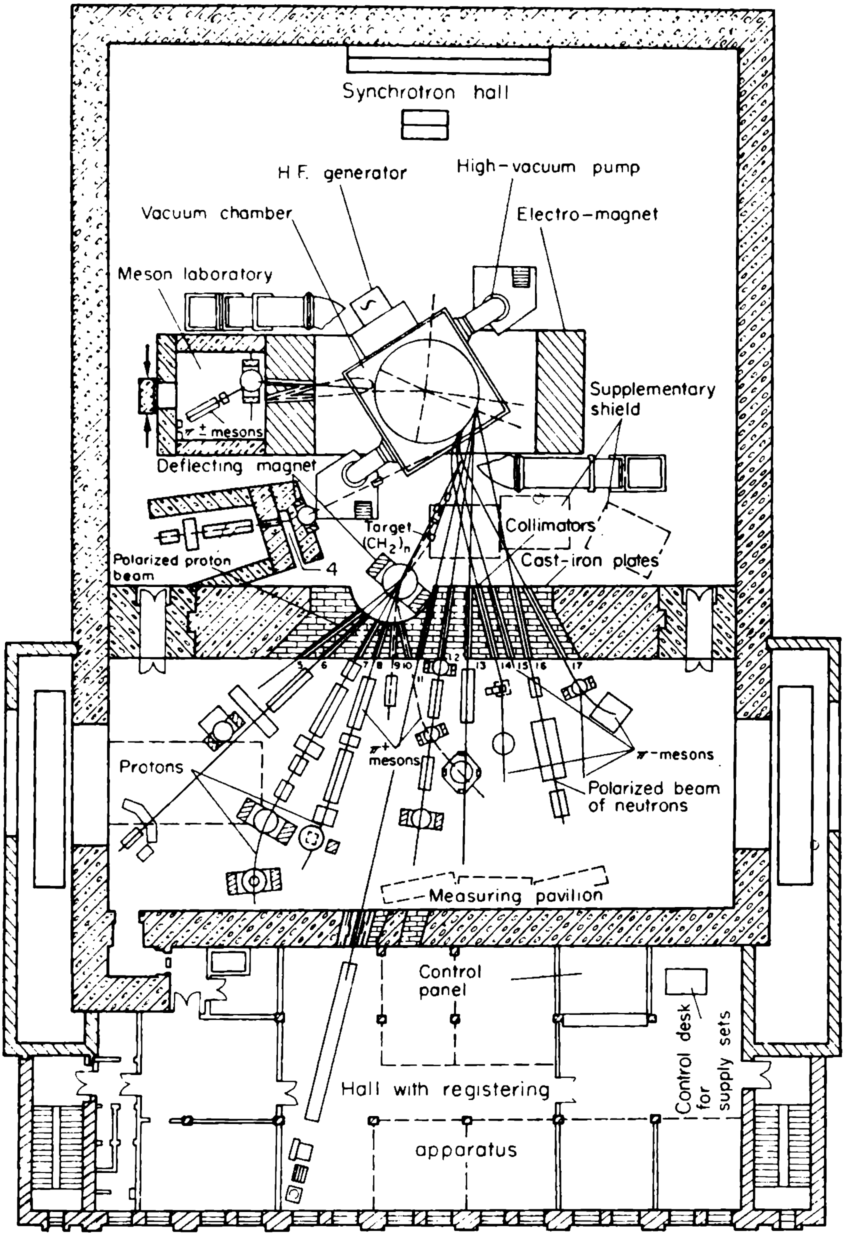


Fig. 40. Arrangement of research apparatus round the 680 MeV synchro-cyclotron.

the charged π-mesons which are formed on a beryllium target situated inside the dee. The intensity of the beam of negative π-mesons here reaches 200 mesons per sec/cm^2.

By the use of phasotrons important investigations are carried out into the reactions between elementary particles and nuclei. The properties and interactions of π-mesons have been studied in detail. One of the most important results obtained with the phasotron was the conclusion that nuclear forces were independent of the charge. Experiments on the scattering of protons and neutrons on protons showed that the proton and the neutron can be regarded as two conditions of one and the same nuclear particle. If we leave out of account those phenomena which depend on the presence of an electric charge on the proton, these particles behave in completely identical ways in the most varied nuclear processes.

The phasotron was the first accelerator to confirm the correctness of Veksler's discovery. Shortly afterwards the construction was begun of another accelerator based on the phenomenon of the auto-phasing of particles. To combat the deleterious influence of the increase of mass of accelerated particles, this accelerator made use of the method of a changing magnetic field.

In the synchroton electrons are accelerated. In its construction it reminds one of the betatron (Fig. 41). The magnet of a synchrotron serves, as in the betatron, for the production of a magnetic flux varying with time; but in the synchrotron the magnetic field is confined to a ring-shaped region near to the orbit of the electrons: it fulfils only the function of controlling the motion of the electrons in a circle. Hence the massive pole of the magnet which fills the whole space is here replaced by a light ring-shaped pole.

The acceleration of the electrons in the synchrotron is produced by an electric field of high frequency. This is generated in a special apparatus—"the resonator"—which is usually part of the accelerating chamber. The resonator is fed from a generator whose wavelength is equal to the length of the circum-

ference in which the electrons rotate. Every time they pass the accelerating gap of the resonator the electrons acquire an energy of several hundred electron volts. The electrons are

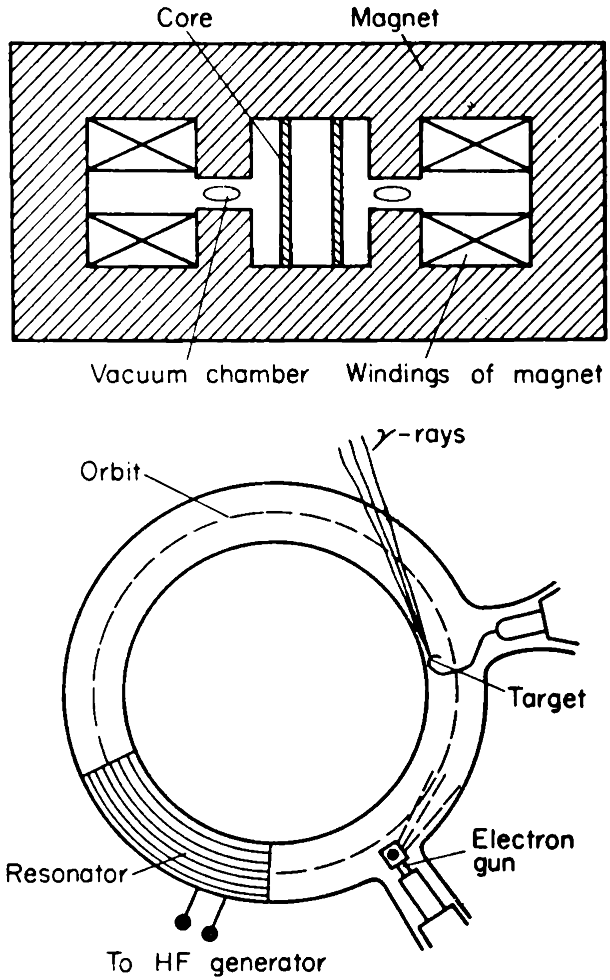


FIG. 41. Diagram of synchrotron.

forced to move with the constant frequency of the electric field, in a circle of almost constant radius. But for this purpose their velocity must be practically constant. We know that even at an energy of 2 MeV the velocity of the electrons becomes very close to the velocity of light ($\beta = 0 \cdot 98$). Hence, before the

acceleration of the electrons by the high frequency electric field, a kinetic energy of 2–3 MeV must be communicated to them. How is this to be done? The so-called betatron starter is generally used for this purpose. A thin steel core is placed in the centre of the magnet which produces the accelerating magnetic field. At the instant when the electrons acquire the necessary energy the core becomes saturated, and up to the beginning of the following cycle plays no further part.

By means of a cathode-oscillograph, a coil placed in the magnetic field, and a particle counter we can obtain a very vivid picture of the process of acceleration in the synchrotron

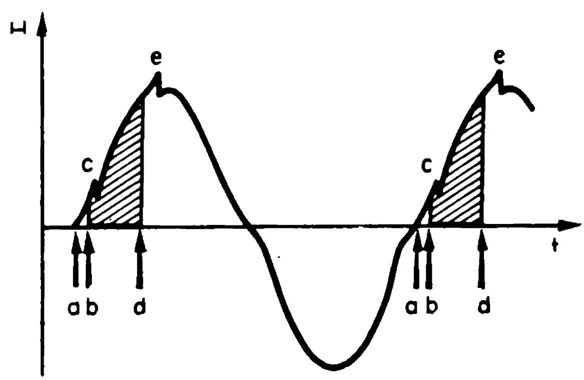


FIG. 42. Process of acceleration in the synchrotron.

(Fig. 42). As in the case of the betatron, the acceleration takes place only in one-quarter of the period of the changing magnetic field, corresponding to an increase in the field. Shortly after the intensity of the magnetic field on the orbit passes through zero, an impulsive voltage is delivered to the electron gun, and electrons are injected into the chamber of the synchrotron (*a*). Not long before the beginning of the saturation of the central core (point *b*) the electric field is switched on and picks up the electrons which have been accelerated only under betatron conditions and not subjected to the subsequent acceleration. The number of such particles is extremely small. The majority of the electrons continue to increase in energy with

the growth of the magnetic field of the synchrotron. After the removal of the voltage from the resonator (the time of the break *d* depends on the energy to which the electrons have to be accelerated) the beam of electrons begins to move inwards in a spiral under the action of the increasing magnetic field, until they strike the target.*

At one point of the oscillogram the peak *e* is seen, due to the counter pulses, corresponding to the bremsstrahlung which arises at the moment when the electron falls on the target.

In small accelerators the electrons can be directed at will on to an external target. For this purpose the high frequency field must be cut off at a moment near to the maximum of the magnetic field. The reduction in H produces an increase in the radius of orbit of the electrons. The back of the electron gun usually acts as an external target.

Synchrotrons are being constructed for enormous energies up to several BeV. The radiation of the electrons, which limits the maximum energy of the particles in the betatron, is in this case less dangerous. The increase in the radiation of the electrons leads to their beginning to take a great deal of energy from the electric field. It is essential to have a sufficient potential difference across the accelerating gap. We have one more convincing example of the remarkable property of the auto-phasing of particles. In addition to the demands which it makes on the high frequency system, which has to make up for enormous radiation losses, the radiation exercises a serious influence on the motion of the particles in the accelerator. As the work of the Soviet physicist A. A. Kolomenskii has shown, in weakly focusing accelerators, where the coefficient of reduction of the magnetic field n is less than one and greater than zero, the radiation leads to an additional damping of the oscil-

* The cause of the movement inwards is not difficult to understand. The energy of the electrons, approximately equal to 300 HR, does not change after the cessation of the acceleration. The increase in the magnetic field H naturally leads to a diminution of the radius of the orbit R.

lations. On the other hand, in strongly focusing accelerators (see below) radiation increases the swing of the oscillations and it is necessary to take special measures to prevent them from building up to excessive amplitudes.

The radiation of the electrons in the synchrotron embraces the region of the visible wavelengths. It can be observed in the form of a bright spot by means of a system of mirrors.

Nuclear transformations produced under the action of γ-rays of various energies are studied with synchrotrons. Plate 4 shows a synchrotron working in the Lebedev Physical Institute in Moscow. It gives a beam of bremsstrahlung with energies up to 265 MeV.

10. THE REBIRTH OF THE LINEAR ACCELERATOR

The first linear accelerators, which were built at the same time as the cyclotron, had little success with physicists for a long time. It was impossible to obtain particles of sufficiently great energy with these accelerators. However, after 1945, linear accelerators came back into people's minds in connection with the development of the technique of short and ultra-short waves. It was now possible to count on obtaining energetic protons and electrons from linear accelerators.

Another reason for the renewed interest in linear accelerators was the discovery of the principle of auto-phasing, which made it possible to work out a new theory of the motion of particles in such accelerators.

Linear accelerators have a particular advantage over cyclic accelerators. It is possible to obtain from them beams of particles of very great intensity. These beams are much easier to use than those of cyclic accelerators, where the removal of the particles from the chamber is a complicated technical problem. Finally, protection from radiation in linear accelerators is considerably cheaper than in cyclical installations.

Proton linear accelerators are as yet not built for energies greater than a few tens of MeV. This is principally to be ex-

plained by the high cost of the powerful generating valves, which become unserviceable comparatively quickly.

Present day linear accelerators for protons work on short waves (about 1·5 m). Hence the whole internal volume of the apparatus, called the resonator or wave guide, takes part in the production of the accelerating electric field. Generators of short waves (magnetrons or klystrons) excite standing electromagnetic waves in the hollow interior of the resonator. The

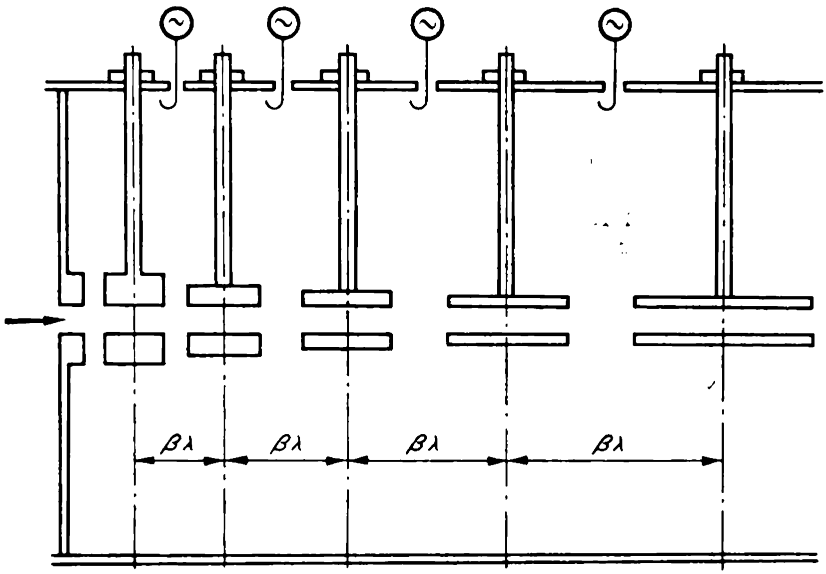


FIG. 43. Linear proton accelerator.

electric field of the waves is directed along the axis of the accelerator, where there is a series of tubes of increasing length (Fig. 43).

The distance l between the centres of the tubes is equal to the product of the relative velocity $\beta = v/c$ and the wavelength of the generator. Hence the protons will arrive in the accelerating gaps after equal intervals of time,

$$t = \frac{l}{v} = \frac{\beta\lambda}{v} = \frac{\lambda}{c}.$$

The auto-phasing of particles also takes place in the linear accelerator, but somewhat differently from in the synchrotron.

Suppose a particle passes through the accelerating gap at a voltage greater than the equilibrium voltage. It will spend less time in its passage to the next gap than the equilibrium protons (since the energy it has acquired is correspondingly greater) and will thus enter a weaker electric field. In consequence its phase will perform stable oscillations around the equilibrium value in the same way as in cyclical accelerators. The difference consists in the fact that in the linear accelerator auto-phasing will occur during the growth and not during the fall of the electric field in the gap. But an increasing field will lead to the focusing of the particles as they pass through the gap, since the de-focusing part of the gap (see page 29) will correspond to an increased electric field. Hence it is necessary to provide special means for ensuring the focusing of the particles towards the axis of the beam. Such focusing is especially important at low velocities (in comparison with the velocity of light). In order to avoid the de-focusing of the protons, a grid of metallic strips is placed at the entrance to each tube. These grids improve the form of the electric field in the gap. The de-focusing region almost completely disappears (Fig. 44). Unfortunately the use of grids produces a noticeable loss of intensity in the beam. Hence, at the present time, other improved methods for focusing particles in the linear accelerator are being worked out. The use of strong magnetic or electrostatic lenses placed along the length of the accelerator produces good results.

For the acceleration of the electrons in linear accelerators metallic tubes, or wave guides, are also used. The wavelength of the electro-magnetic field in this case is still smaller than in proton accelerators, and amounts to approximately 10 cm. This is to be explained by the fact that the velocity of the electrons very nearly approaches the velocity of light. The phase velocity of propagation of electro-magnetic waves in a wave guide is greater than the velocity of light. For success-

ful acceleration the velocities of the waves and the electrons must be equal. In order to reduce the velocity of propagation of the waves, ring-shaped diaphragms are placed within the wave guide. Depending on the load at the extremities of the wave guide, we can obtain two types of waves. If the waves

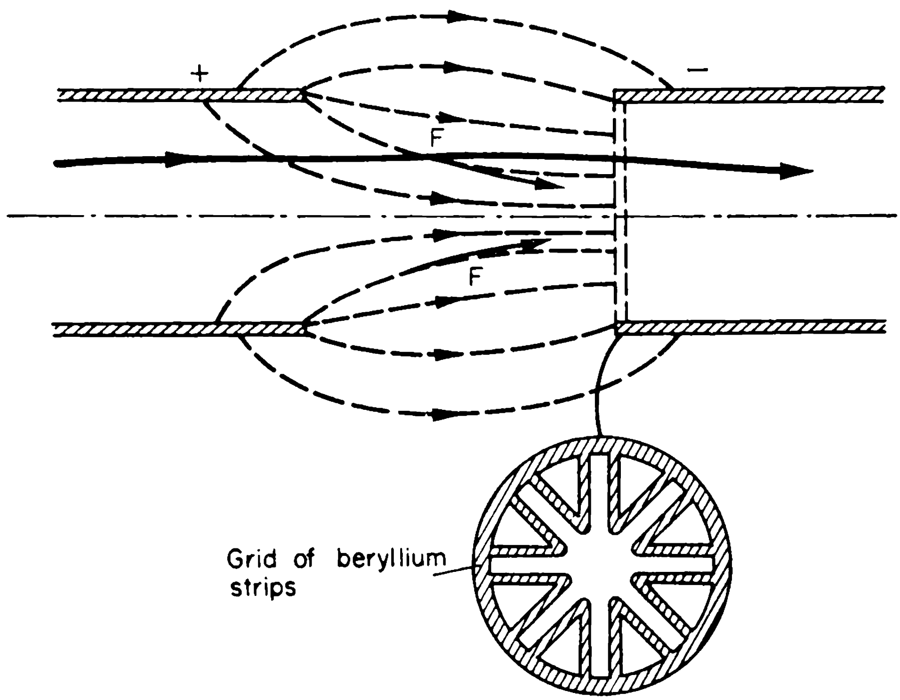


FIG. 44. Action of grids in the linear accelerator.

are reflected from the ends of the wave guide we have standing waves, but if there is no reflection, than a travelling wave is formed. If an electron is carried through the accelerator on the crest of the travelling wave it acquires an enormous energy in a few millionths of a second.

The travelling wave system of acceleration is used in the very large linear electron accelerator at Stamford (U.S.A.). Electrons are accelerated to an energy of 600 MeV in a tube of 7·5 cm diameter and 66 m long. The electro-magnetic field is excited by klystrons for 2 μsec with a frequency of 60 c/s. The power delivered by the generators in each short pulse

amounts to 200,000 kW! The number of electrons accelerated in one pulse is 100 milliards, and the average current of accelerated particles amounts to 1 μA.

Linear electron accelerators are also constructed for the low energies of 5–15 MeV. These instruments, like the betatron, have various applications in medicine and technology.

11. THE SYNCHROPHASOTRON

In principle the acceleration of any particle in the phasotron can be carried out up to very high energies. However, for various reasons it has been necessary to confine ourselves to comparatively modest energies which do not exceed 1 BeV. These reasons are "weighty" in the most literal sense of the word. The weight of the phasotron magnet increases proportionally to the cube of the energy. Hence, in order to construct a phasotron of, for example, 3 BeV, it would be necessary to build a magnet of 300,000 tons weight. The economic and technical difficulty of such an accelerator is obvious.

It will be remembered that the synchrotron has, in comparison with the betatron, a relatively light magnet, because it accelerates the electrons in a narrow ring. Could not heavy particles also be compelled to rotate in the magnetic field in a narrow path instead of in an expanding spiral? The electrons in the synchrotron move in a circle of constant radius because their velocity is almost equal to the velocity of light. The velocity of heavy particles, however, increases continuously with increasing energy. Hence the frequency of their rotation in an orbit of constant radius will also increase. Consequently, in order to preserve resonance with an orbit of constant radius, it is necessary to ensure that the frequency of the accelerating electric field also increases. Thus the acceleration of heavy particles in a ring accelerator requires not only an increase in the magnetic field on the orbit which follows from the formula

$$R = \frac{mv.c}{H.e},$$

but also an increase in the frequency of the electric field. Accelerators of this type have been called synchrophasotrons. As we know, in the phasotron it is not necessary to confine ourselves to a single definite law of variation of the frequency of the electric field. The ions obediently follow any change of the frequency which is not too rapid. The situation is different in the synchrophasotron. Here, in order to maintain the ions in a constant orbit, the frequency of the electric field must be always equal to the frequency of rotation of the ions. However, the frequency of the external field is allowed to deviate somewhat, for example to become greater than the natural frequency of the protons, since their orbit will begin to diminish and threaten to touch the internal wall of the acceleration chamber. This is to be explained by a certain feature of auto-phasing: the frequency of the particles follows the change in the external frequency, but the increase in their frequency of revolution for a given velocity of the protons takes place through a reduction in the radius of their orbit. Hence the change in frequency must exactly follow the change in the velocity of the particle. But it is difficult to fix the velocity exactly. It is much easier to follow the course of the change in the magnetic field which, owing to auto-phasing, on the whole determines the velocity of an ion. Hence in the synchrophasotron a system has been worked out by means of which the frequency of the electric field follows very exactly the changes in the magnetic field.

At the present the most energetic particles are obtained in synchrophasotrons. Three gigantic accelerators of this type are already at work. The first of these, designed for the acceleration of protons to an energy of 3 BeV, was called "the cosmotron". This name underlines the fact that the velocities of the artificially accelerated particles are equal to those of the cosmic rays. A synchrophasotron for 10 BeV has been built in the Soviet Union and delivered to the United Institute of Nuclear Research. In March 1957 protons of the calculated energy were obtained in this accelerator. Let us take an ima-

ginary journey to the town of Dubno, near Moscow, and examine one of the most interesting installations of the present day. It combines enormous size with extraordinary accuracy in the assembly of the individual units and assemblies, which in turn are extraordinarily well thought out. The labour of thousands of workers is embodied in this grandiose installation. We approach a large circular building situated in a pine wood (Plate 5). The first thing that strikes the eye as we enter the building is an enormous electromagnet built of individual sections (Plate 6). Its weight is 36,000 tons. The magnet is constructed of steel sheets of thicknesses 1 and 4 cm insulated one from the other. Although the magnetic field increases comparatively slowly—in 3·3 sec—from zero to its maximum value, it was impossible to build the magnet out of solid continuous metal. The electro-magnet is not a closed ring—it consists of four sections or quadrants separated from each other. Correspondingly, the orbit of the protons is not circular, but consists of four arcs of 90° joined by straight portions (Fig. 45). As both preliminary theoretical calculations and experiments carried out with models have shown, motion in such an orbit is completely stable.

Why are these straight portions, not subject to the action of the magnetic field, necessary in the synchrophasotron? In the first place to make the introduction of the particles easier. As distinct from other accelerators, the particles introduced into the synchrophasotron are already comparatively fast. The protons destined for the synchrophasotron have first been accelerated in a high voltage tube to 600 keV, and then in a linear accelerator to an energy of 9 MeV. The purpose of this is to reduce the range of variation of the high frequency. The velocity, and consequently also the frequency, here increases more than eight times (from 182 kc/s to 1·5 Mc/s). If, however, the acceleration of the particles were begun inside the accelerator from low energies, this would require a variation in frequency which would be technically impossible.

It would be very difficult to accommodate the apparatus for the introduction of the particles with a distance between the poles amounting to only 40 cm. The existence of the straight intervals considerably simplifies this difficult problem of in-

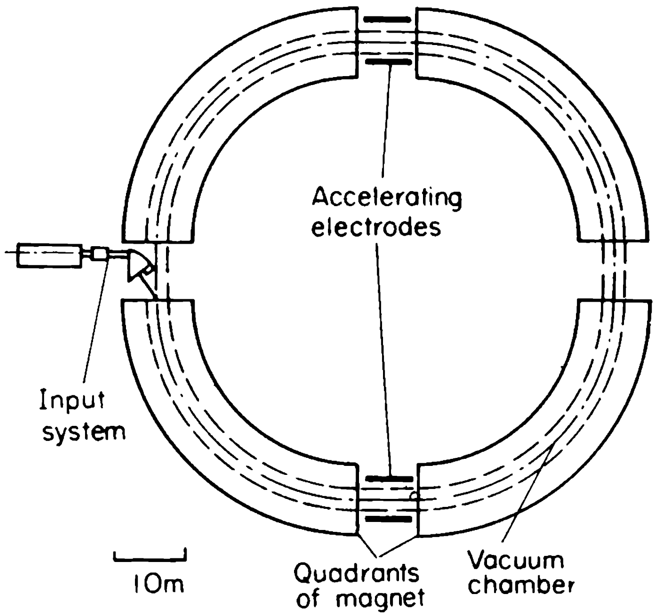


FIG. 45. Plan of accelerator.

troducing the particles into the accelerator. Before passing into the phasotron from the linear accelerator, the particles traverse a 10 m path in the inlet system, which consists of magnetic correctors, a rotating magnet and a magnetic lens (Plate 7). While traversing this path the beam of protons is focused and rotated through 75°. The "injection" of the protons into the chamber takes place at the instant when the magnetic field reaches 150 oersted. An error of even a few millionths of a second in the introduction of the particles is not permissible! A magnetic field of a different value would deflect the particles on to the inner or outer wall of the vacuum chamber. The direction of the beam of particles on entry must be especially accurate; it is corrected with an accuracy of a few

hundredths of a degree: Two other rectilinear intervals contain transit tubes—accelerating electrodes—connected to a high frequency generator. In a single revolution the protons acquire on the average the comparatively low energy of 2200 eV. But during the growth of the magnetic field to 13,000 oersted about 4·5 million protons perform such revolutions in an orbit whose length is 200 m. In only 3·3 sec a proton traverses a path 900,000 km long, i.e. more than twice as long as the distance from the earth to the moon. The whole of this long path is traversed inside the vacuum chamber. The cross-section of the chamber is 2 m wide and 36 cm high. The synchrophasotron has a double vacuum chamber. The outer chamber is formed by the pole shoes of the magnet made airtight with textolite and rubber. In this chamber a pressure of 1 mm of mercury is maintained. The inner chamber is constructed of sheets of stainless steel hardly thicker than a safety razor blade and lagged with special rubber, and a pressure of 0·00001 mm of mercury is maintained inside it. In view of the large cross-section of the chamber, in which a big man could easily lie, one might think that it would not be very difficult to ensure the successful motion of protons in it. However, this is not the case. The important thing is not the width of the chamber, but its ratio to the radius of the orbit; and this is only 4 per cent.

Before constructing this enormous accelerator, physicists carried out complicated theoretical calculations. They considered in detail the motion of the protons from the moment of introduction to the end of the acceleration. The behaviour of the particles proved to be very complicated. In the first place they move in an equilibrium orbit with the resonance frequency. They have also another motion—an oscillation round the resonance orbit which is connected with the auto-phasing of the particles. These radial-phase oscillations are slow, their period being a thousand times greater than the period of revolution of the particles. Owing to the radial-phase oscillations

the protons move in "instantaneous" orbits. Finally, there is a third form of oscillation of the particles—free or betatron oscillations. These arise from deviation of the particles from the orbit, due to the introduction of particles into the accelerator, and to scattering on residual particles of gas, or from other causes. Under the action of the focusing forces the free oscillations are rapidly damped. The calculations of the theorists made it possible to choose the optimal conditions for the introduction of the particles, and the form of the magnetic field, and to explain the causes leading to the possible loss of particles. The most favourable parameters of the accelerator were determined, especially the dimensions of the path in which the protons would move. In order to achieve a motion in this path the huge magnet was constructed with an accuracy of fractions of a millimetre! Special correcting windings on the magnet compensate for distortion due to the influence of the residual magnetism and the saturation of the steel. The relationship between the frequency of the electric field and that of the magnetic field is maintained with an accuracy of 0·1 per cent.

The electro-magnet of the synchrophasotron absorbs the enormous power of 140,000 kVA. The four supply assemblies are provided with massive flywheels. These store up the energy required to produce the current pulses in the electro-magnet. The energy of the magnetic field also returns to them when it falls (save for heat losses). The transformation of mechanical energy into electrical energy and conversely is carried out with the help of synchronous machines directly connected with ionic converters.

Short pulses of protons accelerated to 10 BeV are obtained at the output of the synchrophasotron. These pulses appear five times a minute. In the next chapter we shall dwell upon certain results obtained by physicists working with synchrophasotrons.

CHAPTER V

IN SEARCH OF NEW PATHS

12. SOME RESULTS OBTAINED WITH GIANT ACCELERATORS

In spite of the fact that only a few years have passed since the largest accelerators to milliards of eV first began to work, science has already been enriched by them with remarkable results. With such powerful weapons as the synchrophasotron and the great linear accelerator for the study of the properties of matter, physicists have undertaken interesting investigations. We shall touch upon only two.

About thirty years ago the English physicist Dirac reached the following interesting conclusion as the result of his theoretical researches: there must exist in nature, in addition to the well-known negative electrons, positive electrons with a mass equal to that of the ordinary electron and a charge equal to the electronic charge in absolute magnitude. This result was most unexpected, since up to that time nobody had observed the positive electron. But after only two years Dirac's theory was brilliantly confirmed. The positron—the positive electron—was observed in the cosmic rays and photographed in the Wilson chamber.

By extending Dirac's theory to heavy particles, we come easily to the conclusion that here also, in addition to the ordinary easily observed nuclear particles—the proton and the neutron—there must also exist their opposite numbers. In addition to the proton there must exist the anti-proton—a particle with the same mass and absolute magnitude of charge, and the same nuclear activity, but negatively charged. Along with the neutron there must also be the anti-neutron. Attempts extending over twenty years to observe the heavy anti-particles

PLATE 5. General view of the building housing the 10 BeV synchrophasotron of the United Institute of Nuclear Research.

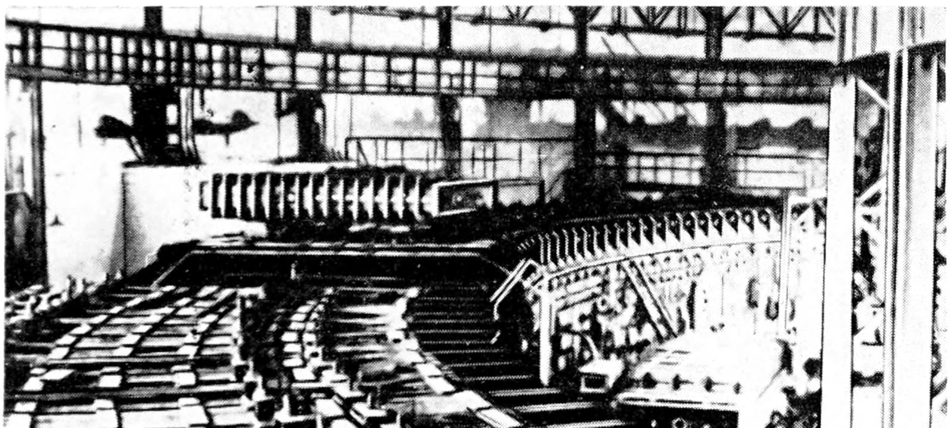


PLATE 6. Part of magnet of 10 BeV synchrophasotron.

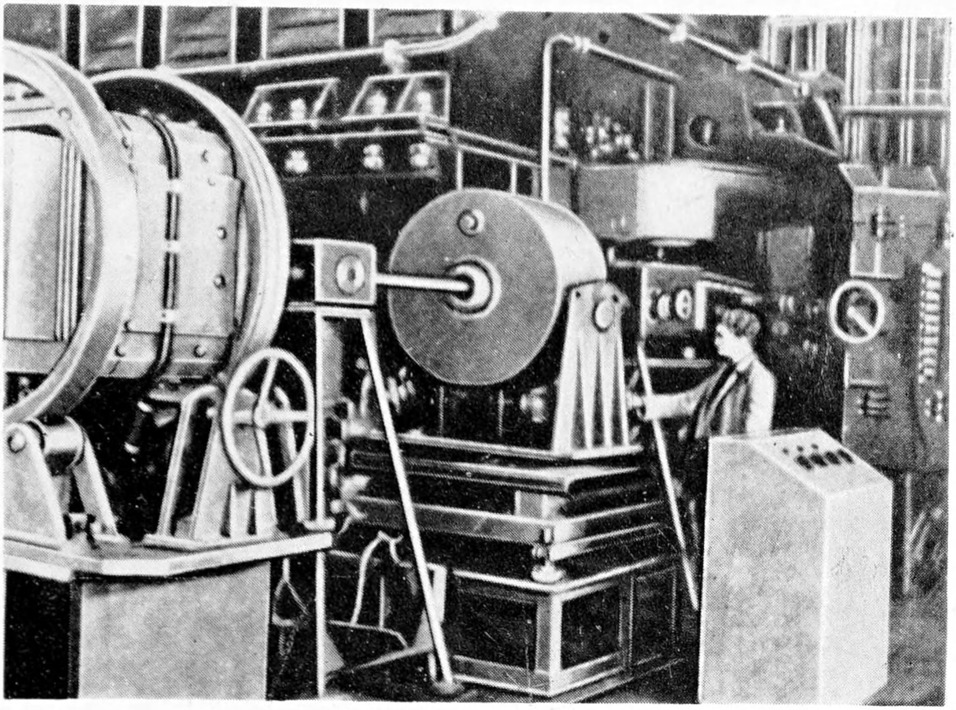


PLATE 7. Inlet system through which particles are conveyed from the linear accelerator to the accelerating chamber of the synchrophasotron.

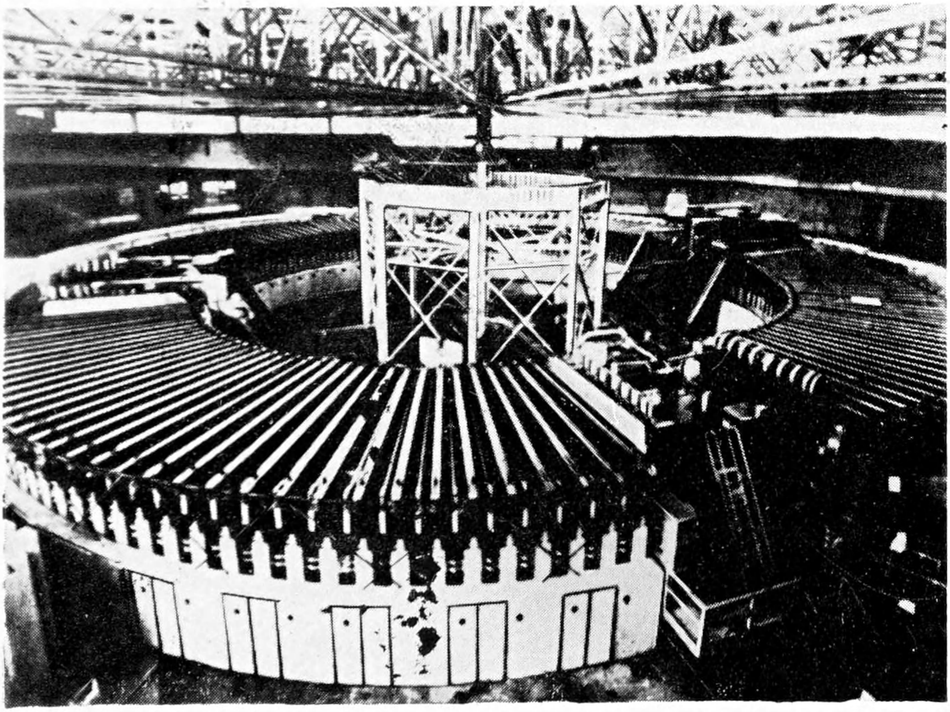


PLATE 8. General view of magnet of the "bevatron" in the synchrophasotron of the University of California (U.S.A.) in which protons are accelerated to an energy of 6.2 BeV.

in the cosmic rays were finally unsuccessful. It will thus be understood why scientists tried to observe the elusive particles with the help of accelerators which gave streams of particles of considerably greater intensity than the cosmic rays. In order to observe the positron an energy was required not less than that corresponding to double the rest mass of the electron, i.e. 1·02 MeV. To observe the anti-proton, finally, an energy a thousand times greater was required. Calculation shows that for the formation of a pair of heavy particles (proton and anti-proton) the energy of the bombarding nucleon must be not less than 4·3 BeV. Until synchrophasotrons for milliards of eV had been constructed there could be no thought of finding the anti-proton. The synchrophasotron built in the United States in the California Institute (it was called the bevatron), was designed for the acceleration of protons to an energy of 6·2 BeV, i.e. to an energy sufficient to obtain anti-protons.

A group of physicists under the leadership of Professor E. Segré spent several years in constructing a complicated apparatus designed for the "capture" of anti-protons.

In August 1955 an experiment aimed at the observation of anti-protons with the bevatron was successfully carried out. Sixty cases were successfully recorded of the passage through the apparatus of particles, with regard to which there remained no doubt. They were anti-protons!

In order to understand the great difficulty of the problem to be solved, we must note the following fact. For each recorded anti-proton there were about sixty thousand negative π-mesons, which also passed through the apparatus. The experimenters had to distinguish clearly the isolated events in which they were interested against the background of an enormous number of confusing events. We cannot describe these remarkable experiments in detail. Hence we will endeavour only to explain the general idea. Figure 46 shows a diagram of the experiment for observing anti-protons. The apparatus consists of a system of magnets and magnetic lenses placed one

after the other, interspersed with a number of particle counters. Protons accelerated in the bevatron to an energy of 6·2 MeV bombarded the copper target *T*. The system of magnets and lenses made it possible to separate a beam of negatively charged particles possessing strictly identical momentum ($p = mv$, where m is the mass of the particle and v is the

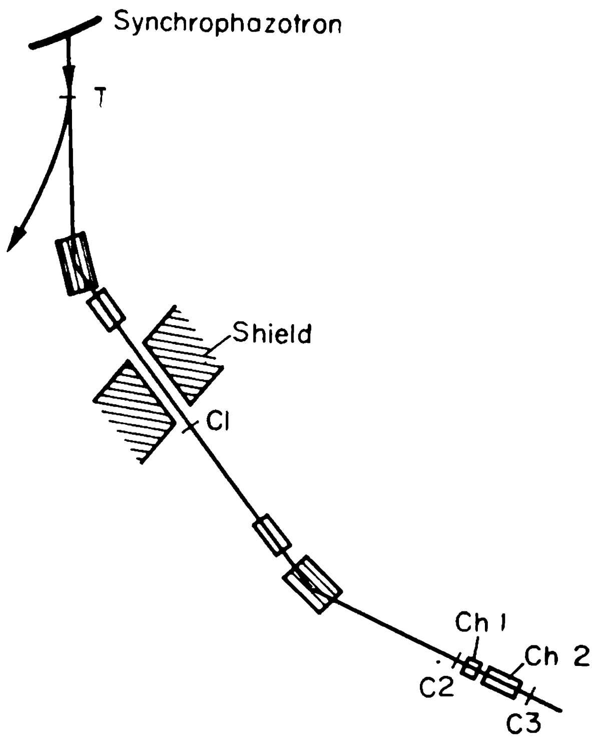


FIG. 46. Diagram of experimental attempt to observe anti-protons.

velocity). In order to determine the mass of the particle for a given momentum it was necessary to know its velocity. This was the purpose of the system of counters. Since the anti-protons had to be picked out against a dense background of mesons, the measurement of the velocities had to be carried out by different methods. We must say something about the counters which played a very important part in the experiment. They were of two kinds. Some were scintillation counters (*C1*,

C2, *C3*), similar in principle to the apparatus used by Rutherford in his first experiments. The difference was that whereas formerly the scintillations were observed by the eye, they were now registered by a very sensitive instrument—the electronic photo-multiplier. In addition to making the task of the experimenter easier, this substitution made it possible to determine with very great accuracy (up to 10^{-9} sec) the instant when a particle passed through the counter. The first method of determining the velocities of the particles was based on this property of the scintillation counters. Two counters, *C1* and *C2*, were separated by a distance of 12 m. This distance was traversed by a π-meson with the given momentum in 0·4 μsec, and by the heavy anti-proton in 0·51 μsec. A radio circuit was so constructed that it came into action only when the time of flight of a particle between the two counters *C1* and *C2* amounted to 0·51 μsec. In this way the unneeded π-mesons were sifted out. The principle of the other group of counters, *Ch1*, *Ch2* was based on a phenomenon discovered by the Soviet physicist P. A. Cherenkov in S. I. Vavilov's laboratory. This was the phenomenon of the radiation of light by an electron which was flying through a substance with a velocity greater than the velocity of light in that substance. The nature of this phenomenon was also explained by the Soviet scientists I. E. Tamm and I. M. Frank.

The light radiated by the electron in the Cherenkov counter, as in the scintillation counters, was recorded by means of a photo-multiplier. By constructing the counter of transparent materials which transmitted light with different velocities, it was possible to render it sensitive to particles with definite speeds. This property of the Cherenkov counters was also made use of by the physicists who were looking for anti-protons, as a second means of distinguishing particles by their velocities. The counter *Ch1* recorded all particles with a velocity greater than 0·79 c ($\beta = v/c = 0{\cdot}79$). Thus it did not react to the passage of anti-protons. The other counter *Ch2* counted particles of a definite velocity (β less than 0·78 but

greater than 0·75), exactly that which the anti-proton ought to possess. A radio circuit recorded only events counted by counter *Ch2* and not those counted by *Ch1*.

We have described here by no means all the apparatus used in this research. But from what has been said the complexity of the experiment can be imagined.

Still more difficult was the work of observing the anti-neutron carried out quite recently with the same accelerator—the bevatron. The anti-neutron, like the ordinary neutron, has no charge and hence is extremely difficult to observe. Only in one respect was this research easier than the first. After the discovery of the anti-proton the existence of the anti-neutron was subject to no doubt in the minds of physicists.

We shall not describe these extremely complicated experiments. We will only say that the anti-neutron was observed in the process of its annihilation—or disappearance. We know that the positron and the electron together form γ-quanta. The energy evolved in this process amounts to $\sim$ 1 MeV. In the annihilation of an anti-neutron by a neutron π-mesons are formed. These also are recorded by a counter. This process is very difficult to observe accurately, since it is extremely rare. It suffices to say that during the registration of 300 anti-protons only 1 anti-neutron was successfully observed.

The other experiments which we wish to recount were carried out on a giant linear electron accelerator and were concerned with a quite different problem of nuclear physics. Even in Rutherford's first experiments on the scattering of α-particles by gold the approximate dimensions of the nucleus were successfully determined. But how was the charge distributed inside the nucleus? What were the dimensions of the lightest of the nuclei—the hydrogen nucleus or proton? Until recently science has been unable to answer these questions. In the physics of the atom the following very important law was observed: the less the dimensions of an object which was to be studied, the greater the energy of the particles by which this object was investigated had to be. For the observa-

tion of the atomic nucleus the energy of the α-particles from radioactive nuclei was sufficient. In order to investigate the proton, electrons with an energy of hundreds of MeV were required. Actually the dimensions of the apparatus increased by many times in comparison with that of Rutherford. A beam of electrons from a linear accelerator, with an energy of 550 MeV, is displaced from its original position by special

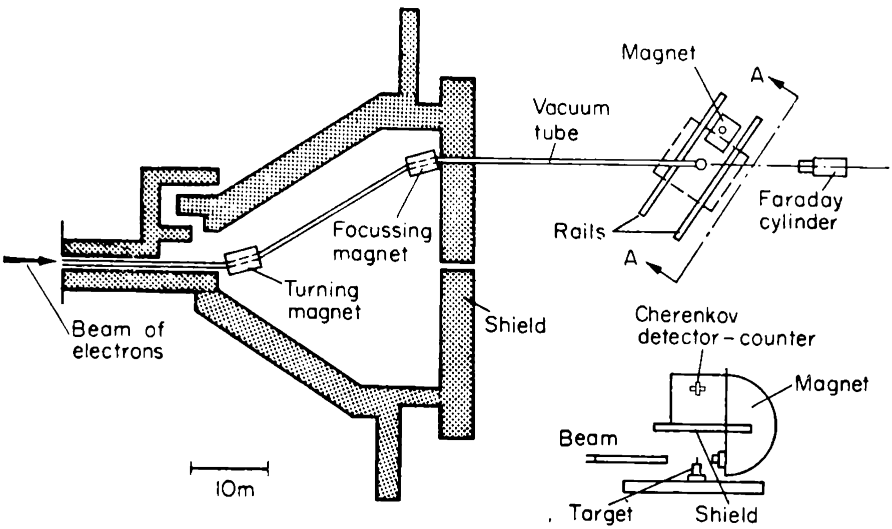


FIG. 47. Experimental determination of dimensions of proton.

magnets over several metres (Fig. 47), and falls on a target of polyethylene, which contains hydrogen. By means of a huge forty-ton magnetic spectrometer only those electrons are selected which have been scattered on protons, thereby changing their direction without losing energy. By rotaing the spectrometer round the target to different angles, the experimenters measured the angular distribution of the elastically scattered electrons and compared it with the distribution calculated theoretically on the assumption that the whole charge of the proton was concentrated at one point. It turned out that at large angles the number of electrons deviated was nine times less than had been expected. From these results it was

possible to find the distribution of the electric charge in the proton. It is illustrated in Fig. 48. We see that the effective radius of the charge on the proton is approximately equal to $0 \cdot 8 \times 10^{-13}$ cm. The distribution of the charge in heavier particles has also been investigated. It has been shown that

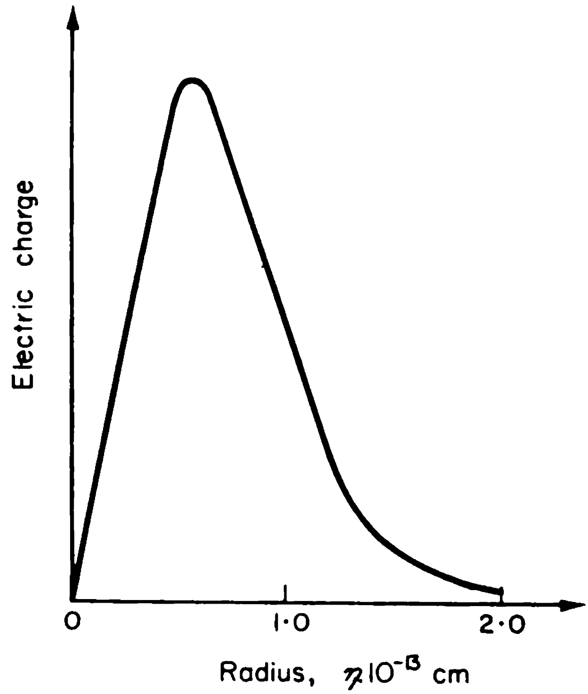


FIG. 48. Distribution of electric charge in proton.

the distribution of the charge is approximately constant within the nucleus. But in all nuclei there is a surface layer where the density of the charge sharply increases. The radius R of any nucleus can be found from the expression $R = (1 \cdot 07 \pm \pm 0 \cdot 2)\ A^{1/3} \times 10^{-13}$ cm. Here A is the atomic number of the nucleus.

13. ONE MORE STEP UPWARDS

In the synchrophasotron, protons with energies of 10 BeV have been obtained. Would it be impossible to attain still higher energies? Such an increase would be very attractive to phys-

icists. Besides increasing the probability of observation of various rare processes, such an increase might make it possible to discover nuclear processes hitherto unknown.

The construction of still larger synchrophasotrons is possible in principle. However, the cost of producing them and the technical difficulties would be extremely great. Remember that the weight of an accelerator to 10 BeV amounts to 36,000 tons. It would be very desirable to reduce the weight of the magnet. This could be done in only one way: by reducing the dimensions of the ring in which the protons move. But in order to reduce the working region it would be necessary to reduce also all the possible oscillations of the protons round the stable orbit. Hence it would be necessary to increase sharply the focusing forces. The problem of obtaining strong focusing has been solved by Kristophilos in Greece and independently by the group of American physicsts, Livingstone, Courant and Sneider. They discovered that the focusing forces could be increased by tens of times by constructing electro-magnets of a special form. The magnet of an accelerator with strong focusing consists of several tens of separate sectors. For some sectors the magnetic field decreases rapidly along the radius, and for others, on the other hand, the field rapidly increases along the radius: the factor of reduction n is of the order of tens or even hundreds. The sectors with falling and rising fields alternate with each other. Remember that a large value of n corresponds to good focusing in height but produces de-focusing in the radial direction. A magnet with an increasing magnetic field and a negative value of n produces strong focusing along the radius but also leads to de-focusing in height. The combination of these very different magnets proved to be extremely effective. The first strongly focusing synchrotron accelerator for 1·2 BeV is already working at the present time. Its data are remarkable. The weight of the magnet amounts to only 20 tons. The cross-section of the acceleration chamber is very small: the gap between the poles is 3 cm, and the width of the chamber 7 cm for an orbital radius of 4 m.

Notice that the factor of reduction of the magnetic field is at first small ($n = 20$). A study of the working of the accelerator shows that even with such a small working space the greater part of the space is not used. Even at electron energies of 100 MeV the beam is compressed into a narrow cord 1 mm wide. Accelerators with strong focusing demand extraordinary accuracy in assembling, so that the adjustment of the first such accelerator took more than eighteen months. At the present time several accelerators with strong focusing are under construction in different countries, calculated for particle energies from 25–50 BeV.

At the end of 1959 in Geneva a synchrophasotron was started up which accelerated protons to an energy of 30 BeV, built with the co-operation of several European countries. The magnet of this accelerator is carried on a special base—a concrete ring supported on steel piles 18 m long driven into the rocky ground. This construction will ensure an accuracy of 1 mm in the magnet, whose radius is 100 m. The cross-section of the accelerating chamber is 8×16 cm. Figure 49 shows a cross-sectional view of the Geneva synchrophasotron for 30 BeV (*A* is the electro-magnet, *B* the accelerating chamber, *K* the accelerating element, *E* a structure for the suspension of the base, *F* a support, *L* a magnetic lens).

In the Soviet Union the design of an accelerator calculated for protons with an energy of 50–60 BeV has been completed. The length of the accelerating chamber is about 1½ km. One of the serious defects of the accelerator with strong focusing must be considered to be the existence of a critical energy E_{cr}. When the protons reach the energy E_{cr} auto-phasing disappears. It is true that with a further increase of energy the auto-phasing reappears, but the transition through E_{cr} is a complicated technical problem and involves loss of particles.

But apparently even strong focusing does not enable us to reach an energy higher than 100 BeV. The following example well illustrates the limitations of the accelerators at present in use. In order to obtain in a synchrophasotron particles with

an energy near to the maximum energy found in the cosmic rays (10^{16} eV), its magnet would have to girdle the earth along the equator. Hence any further increase in the energy of the accelerated particles requires new methods of acceleration. We shall deal with several ideas in this sphere at the end of this chapter.

How fast is science advancing in the artificial production of high energy particles? Let us draw a graph in which the years

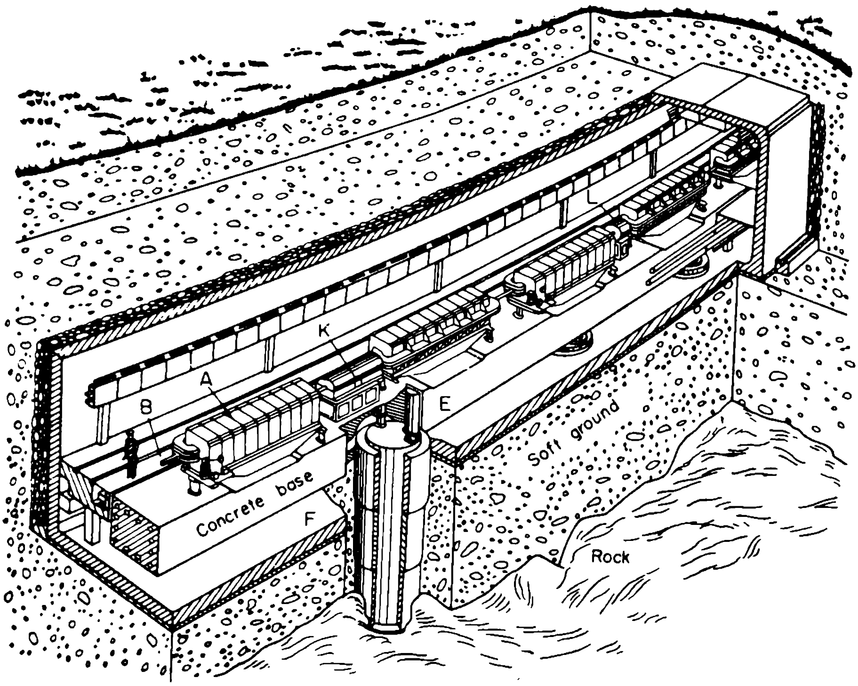


FIG. 49. Sectional diagram of 30 BeV synchrophasotron.

are laid off along the horizontal axis and along the vertical axis the highest energy of the particles accelerated by the accelerators which have been set going in the year. The line connecting the individual points rises so steeply that the energy has to be laid off on a logarithmic scale (Fig. 50). If this dizzy increase continues into the future, then in 1990 an accelerator for 10^{16} eV will be constructed. But what is happening to the intensity of the beams of the accelerated particles? Let us lay

off on the same diagram, on the vertical axis on the right, also on a logarithmic scale, the current obtained in the accelerators. We obtain a relationship similar to the first but tending downwards. In the cyclotron the currents amounted to milli-amperes, in the phasotron and the linear accelerator to micro-amperes, and in the synchrophasotron to milli-micro-amperes. If the law

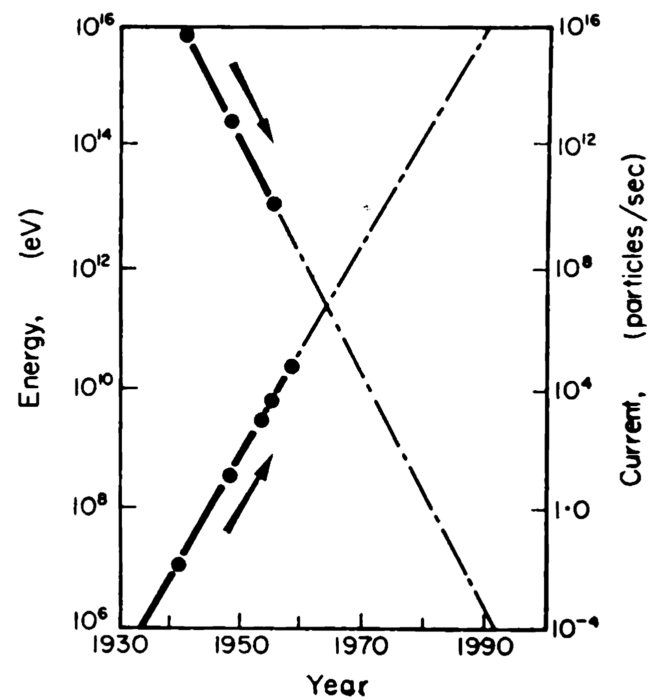


FIG. 50. Graph of change in energy and intensity of accelerated particles.

of change of the intensity does not alter in the years immediately ahead, then in the accelerator to 10^{16} eV only two protons per hour will be produced. In that case accelerators will lose their principal advantage over the cosmic rays: the high intensity of the beam. That is why attempts are being made at present in many laboratories to increase the intensity of the accelerator. In particular it is proposed to increase by ten or more times the limiting energy of the ions in the cyclotron,

where the greatest intensity for cyclical accelerators is attained. It is possible to construct magnets with poles of a special rather complicated form. The Soviet physicists E. M. Moroz and M. S. Rabinovich have proposed a split form for the magnet of a cyclotron, consisting of wedge-shaped sectors. Then, for part of the time, the particles will be in regions where there

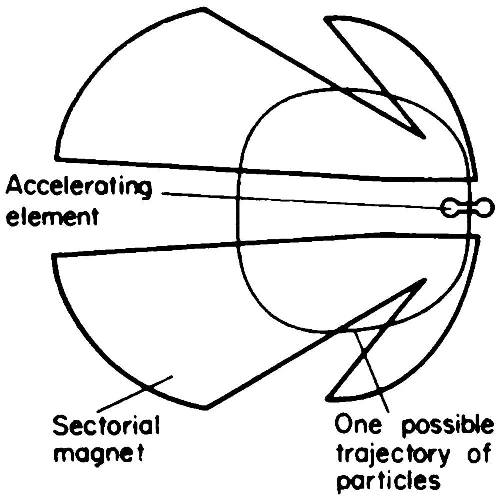


FIG. 51. Diagram of accelerator with constant magnetic field and contiguous orbits.

is no magnetic field. By choosing the form of the sectors in the appropriate way, it is possible to obtain a constant period of revolution for the particles in spite of increasing mass.

Figure 51 shows the form of the permanent magnet proposed by E. M. Moroz for an accelerator, and the corresponding orbits. A very promising idea from the point of view of increase of intensity was put forward some years ago in the Soviet Union by A. A. Kolomenskii, V. A. Petukhov and M. S. Rabinovich, and later by the American physicists Simon and Kerst. It was proposed to construct accelerators with ring-shaped direct current magnets and strong focusing. These accelerators successfully combined the advantages of a constant magnetic field (simplicity and high intensity) and those of the

ring-shaped accelerator (lower weight and cost). Let us consider the working principles of one of these accelerators—the ring phasotron. Its magnetic system (Fig. 52) consists of separate sectors with fields which change very rapidly along the radius.

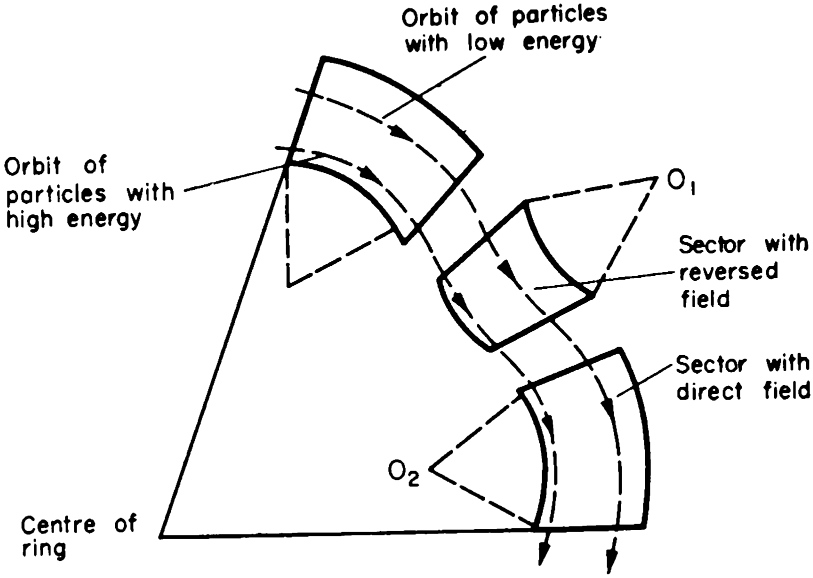


FIG. 52. Working principles of the ring phasotron.

In contrast with the accelerator described above with strong focusing, in which an increasing field alternates with a decreasing field, in the ring phasotron the magnetic field maintains its direction of change along the radius. Only the sign of the magnetic field changes from sector to sector (if in one sector the field is directed downwards, in the next section it is directed upwards). Hence the centres of curvature of the sections of the orbit lie in contiguous sectors on different sides of the path. If for one of these sectors (O_1) the field increases along the radius ($n_1 < 0$) then for the following sector (O_2) it will decrease ($n_2 > 0$). In this way the production of strong focusing is ensured in the ring phasotron. The introduction of portions with oppositely directed fields leads to a lengthening of the orbit by two or three times, which is disadvantageous in

an accelerator. In a ring-phasotron with a magnetic field falling from the centre of the ring (the "reversed" variant) the serious defect of strongly focused accelerators arising from the critical energy (E_{er}) is successfully avoided. In the ring phasotron, generally speaking, the critical energy does not exist.

A new method of obtaining high energy particles has been proposed quite recently. The problem of obtaining beams of high intensity is especially important from the point of view of this proposal. Imagine two beams of high energy particles moving in opposite directions (Fig. 53). Let the energy of the

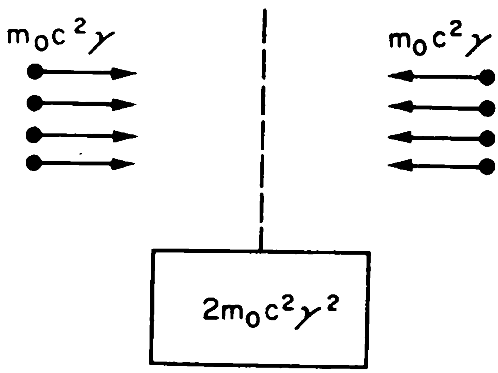


FIG. 53. Collision of oppositely directed beams.

particles in the beams be the same and equal to $m_0c^2\gamma$, where $\gamma = \dfrac{1}{\sqrt{(1-\beta^2)}}$. Let us consider the collision of the beams in a system of coordinates connected with one of them, i.e. in a system in which the particles of one beam are at rest. From the theory of relativity it follows that in this system of coordinates the energy of the particles of the second beam will be very great and equal to 2 $m_0c^2\gamma^2$. Thus in the collision of two beams of protons accelerated to 10 BeV and moving towards one another, processes will occur analogous to what would happen if protons with an energy of 200 BeV fell upon an immovable target. This extraordinary possibility of increasing the energy of the particles cannot yet be used, unfortunately, owing to

the negligible probability that the particles of the two beams will collide. The fact is that in any solid target the number of nuclei is milliards of time greater than in a beam. Thus it is necessary considerably to increase the intensity of the beam. A recent journal contained a very clever proposal for avoiding the difficulty arising from insufficient intensity. The author proposes to collect protons accelerated in a hundred successive cycles by a synchrophasotron of 3 BeV. For this purpose collecting rings have been contrived—permanent ring-shaped magnets (*A* and *B*), placed near to the main accelerator (Fig. 54). A special deflecting system directs the protons alter-

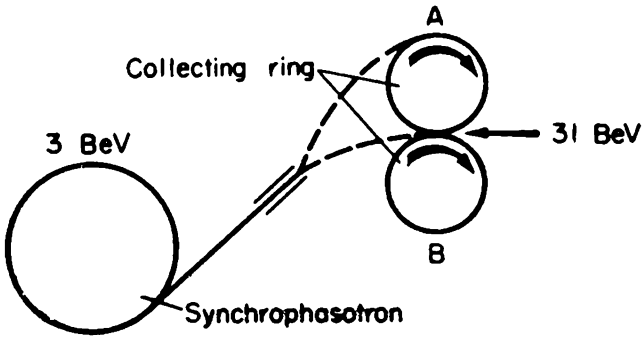


FIG. 54. Synchrophasotron with accumulating rings.

nately to one and the other magnet; after several seconds of accumulation (the accelerator gives 20 c/s) a collision will occur.

This very simple and at first sight attractive idea presents at the same time a complicated technical problem.

In conclusion we must indicate one more line in the construction of accelerators, although it is hardly likely to lead to an increase in the energy of the particles. In all the cyclical accelerators hitherto considered, the magnetic field was produced by means of magnets made of iron. Hence the magnetic field on the orbit was limited to a value of about 15,000 oersted, since at greater fields saturation of the iron takes place. But it is well known that a magnetic field can be produced even

without iron. In this case its magnitude can be raised to 100,000 oersted and higher. A few such iron-less accelerators have been constructed in several countries. In one of these accelerators, an iron-less synchrotron for 300 MeV, the magnetic field is produced by powerful currents. The greatest difficulty in the construction of magnets of this type lies in the problem of compensating for the enormous mechanical forces in the conductor. In Australia at the present time an iron-less synchrophasotron for 10 BeV is under construction. The magnetic field on the orbit with an amplitude of 8000 oersted is produced by the passage of a current of six million amperes through the conductors. It is interesting that in this case the mechanical forces in the windings reach 16 tons/cm length.

14. ACCELERATORS OF THE NEAR FUTURE

Existing methods of accelerating particles permit us to count on reaching energies of 100 BeV in the near future. In order to climb still higher on the energy "ladder" we need new methods and new ideas. Scientists in many laboratories and different countries are working on the problem of producing still more powerful accelerators. Let us consider briefly the researches of two groups of Soviet physicists. It is possible that the development of these investigations may enable the technique of accelerators to advance.

It is well known that in the cyclical accelerators the energy of the particles is determined by the magnitude of the magnetic field. If we could succeed in increasing by tens of times the magnetic field on the orbit of the accelerated particles, without detriment to the conditions of focusing of the beam, a corresponding increase in the energy of the particles would be secured. Attempts to obtain powerful magnetic fields by the use of iron-less accelerators meet with serious constructional difficulties. The Soviet physicist Budker proposes to solve this problem in a quite different way. According to his idea, the magnetic field should be produced by a circular electronic beam of the kind which is formed in the betatron.

In order that the electronic beam should be able to perform such an unusual function, it must differ considerably from that of the betatron. In the first place the number of accelerated electrons must increase thousands of times. Furthermore the density of the electrons in the beam must be enormous—the beam must be compressed into a thin cord with a diameter of a few hundredths of a millimetre. How is this to be done? As we know there are powerful forces of electrical repulsion between the electrons. It turns out that when the velocity of the electrons approaches that of light their mutual repulsion considerably diminishes (by γ^2 times, where $\gamma = \dfrac{1}{\sqrt{(1-\beta^2)}}$. In order to destroy completely the repulsion between the electrons, a small number of positive ions is added to the beam. The radiation by the electrons in the beam leads to the appearance of forces which compress the beam. But radiation also produces a reduction in the energy of the electrons. In order to prevent this, a small betatron accelerating magnetic field is superimposed. Apparently an electronic beam of this kind is a stable and extremely durable formation. Hence it has been called by the author a stabilized electronic beam.

A stream of electrons with an energy of 15 MeV and a current of 1000 A produces the colossal magnetic field of 50,000 oersted near the surface of the beam. On the axis of the beam, at a distance of only 0·04 mm from its surface, only an external magnetic field amounting to 500 oersted exists. It is proposed to use this enormous magnetic field, which falls very rapidly along the radius, for the acceleration of protons. For this purpose the protons must be introduced into the electron beam and accelerated by means of a resonance apparatus of the ordinary type. The protons will at first rotate about the axis of the beam and then, with increasing energy, they will approach nearer and nearer to its surface. During acceleration to an energy of 1 BeV the radius of the orbit of the protons will increase by only 0·04 mm.

It is interesting that in such an accelerator a super-focusing of the protons will be produced, a thousand times exceeding the focusing in the strongly focusing accelerators. This can be explained from the specific conditions of motion of particles within an electron beam under a magnetic field increasing very rapidly in the direction of the radius ($n \sim 10^6$). The beam of electrons and positive ions is as though clamped together by its own electric and magnetic fields. The prospects of the proposed methods of acceleration can be explained by the following example. A current of electrons of 10,000 A rotating in an orbit with a radius of 3 m with an electron energy of 15 MeV makes it possible to accelerate protons to an energy of 100 BeV. The principal difficulty in carrying out the new method consists in obtaining a large current of energetic electrons. Hitherto only preliminary results have been obtained: a current of electrons with an energy of 3 MeV, amounting to 10 A.

Completely new methods of acceleration are being worked out at present by V. I. Veksler and his collaborators. In all existing accelerators the particles acquire energy in an electric field produced by an external source. The intensity of the accelerating field is practically independent of the number of accelerated particles. Naturally in this case the acceleration of each individual particle is independent of the number of particles accelerated.

The special feature of the new method proposed by Veksler lies in the fact that the electric field which accelerates the particles arises from the interaction of a geometrically small group of accelerated particles with another group of charges or an electro-magnetic wave.

It thus proves that in a number of cases the magnitude of the accelerating electric field is proportional to the number of particles. Hence also the name of the method—the coherent method, which is taken from optics, where the same name is given to oscillations which take place with a constant phase

difference, and where each of two coherently operating sources radiate twice as much energy as in the absence of its neighbour.

There are several variants of the coherent method of acceleration. Let us consider one of them. Suppose we have a beam of relativistic particles with a total mass M_1, falling on to a collection of particles at rest with mass M_2. It can be shown that if the condition $M_1 \gg M_2\gamma$ is fulfilled, the stationary group will receive an enormous energy equal to $M_2c^2.\gamma^2$. Thus if a relativistic beam of a great number of electrons with energies of 50 MeV ($\gamma = 10^2$) falls on a stationary group of protons, each proton can acquire an energy equal to $10^9 \times (10^2)^2 = 10^{13}$ eV. In this method the main difficulty is to obtain groups containing a huge number of particles, which is opposed by the coulomb repulsion of the charges in the group. The various aspects of the new method are being carefully studied.

Here we have briefly considered the principal forms of charged particle accelerators. The further development of science and technology will undoubtedly lead to the construction of new, still more perfect forms of apparatus which will help mankind to control the forces of nature.

REFERENCES

1. E. Fermi, *Lectures on Atomic Physics*, IL, 1952.
2. E. Pollard and V. Davidson, *Applied Nuclear Physics*, Gostekhizdat, 1947.
3. G. Bethe and F. Morrison, *Elementary Theory of the Nucleus*, IL, 1958.
4. M. Korsunskii, *Atomic Nucleus*, Gostekhizdat, 1956.
5. V. Gol'danskii and Ye. Leikin, *Transformation of Atomic Nuclei*, Akad. Nauk SSSR, 1958.
6. A. Grinberg, *Methods of Accelerating Charged Particles*, Gostekhizdat, 1950.
7. V. Veksler, *Accelerators of Charged Particles*, Akad. Nauk SSSR, 1956.
8. M. Livingstone, *Accelerators*, IL, 1956.
9. P. Kapitsa, *Reminiscences of Rutherford*, U.F.N. 19, 1, 1938.

APPENDIX

PRINCIPAL TYPES OF

Type of accelerator	*Particles accelerated*	*Shape of orbit*	*Magnetic field (in time)*
High voltage accelerators	Any	Rectilinear	—
Linear electron accelerator	Electrons	Rectilinear	—
Linear proton accelerator	Heavy particles	Rectilinear	—
Cyclotron	Heavy particles	Spiral	Constant
Betatron	Electrons	Circular	Increasing
Phasotron	Heavy particles	Spiral	Constant
Synchrotron	Electrons	Circular	Increasing
Synchrophasotron	Protons	Circular	Increasing
Accelerators with strong focusing	Protons	Circular	Increasing

† Rough estimate

	Frequency of accelerating electric field	*Continuous or impulsive acceleration*	*Mean current of accelerated particles*†	*Maximum energy*	*Limitation on energy*
	—	Continuous	$\sim 10^{-3}$ A	$\sim$ 10 MeV	Discharges
	Constant	Impulsive	$\sim 10^{-6}$ A	a few BeV	Cost
	Constant	Impulsive	$\sim 10^{-8}$ A	$<$ 1 BeV	Cost
	Constant	Continuous	$\sim 10^{-3}$ A	$\sim$ 25 MeV	Change of mass
	—	Impulsive	$\sim 10^{-6}$ A	300 MeV	Radiation loss and cost
	Modulated	Impulsive	$\sim 10^{-6}$ A	$\sim$ 1 BeV	Cost
	Constant	Impulsive	$\sim 10^{-6}$ A	a few BeV	Radiation loss and cost
	Increasing	Impulsive	$\sim 10^{-9}$ A	$\sim$ 10 BeV	Cost
	Increasing, then constant	Impulsive	$\sim 10^{-9}$ A	$\sim$ 100 BeV	Cost

INDEX